University of Zagreb

FACULTY OF KINESIOLOGY

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BIOMECHANICAL GAIT AND STANCE PATTERNS UNDER DIFFERENT LOADS OF OFFICIAL EQUIPMENT OF INTERVENTION POLICE UNIT OFFICERS

DOCTORAL THESIS

Zagreb, 2025.

Sveučilište u Zagrebu

KINEZIOLOŠKI FAKULTET

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Supervisor:

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Mentor:

prof. dr. sc. Mario Kasović

Zagreb, 2025.

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1. DECLARATIONS

I, Davor Rožac, hereby declare that this thesis entitled "Biomechanical gait and stance patterns under different loads of official equipment of Intervention Police Unit Officers" is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma at any university or equivalent institution. I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation, and linguistic expression is acknowledged. Where applicable, any part of this thesis containing materials prepared jointly with others has been explicitly identified. This doctoral research is comprised of three studies with interconnected research aims. The studies resulted in four scientific articles published in international peer-reviewed journals that are included in this thesis. All four articles were published after my enrolment in the doctoral programme. In the thesis, I used the American Psychological Association (APA) 7th edition style of referencing. References from all chapters are presented alphabetically in the "References" chapter. All three studies were conducted in accordance with the Declaration of Helsinki. In addition, all participants provided written informed consent to participate in the study. This study was approved by the Ethical Committee of the Faculty of Kinesiology and the Police Intervention Department under the Ministry of Internal Affairs of the Republic of Croatia (Ethical code:511-01-128-23-1). Any views expressed in this thesis are those of the author and do not necessarily reflect the views of University of Zagreb, Faculty of Kinesiology or any other institution.

2. SUPERVISOR INFORMATION

Mario Kasović was born on June 18, 1970, in Zagreb (Croatia). He is a full professor at the Faculty of Kinesiology at the University of Zagreb. He graduated in 1998, at the University of Zagreb, Faculty of Physical Education, thereby obtaining a university degree and the professional title of Professor of Physical Education, as well as an additional professional qualification for work in Kinesitherapy. In 2004, he earned the academic degree of Master of Science in the field of social sciences, the scientific field of educational science Kinesiology. The academic degree of Doctor of Science in the field of social sciences, the field of educational sciences - branch of kinesiology, obtained by defending his doctoral dissertation on March 4, 2009, entitled "Biomechanical assessment of anterior cruciate ligament reconstruction". In January 2001, he was appointed as a junior researcher on the project “Neuromuscular biomechanical diagnostics of sports and pathological locomotion” led by Professor Vladimir Medved and to the course Biomechanics at the University undergraduate study program at the Faculty of Kinesiology in Zagreb, where he participates in teaching. The Government of the Republic of Croatia, at its session held on June 6, 2013, appointed Professor Mario Kasović as a member of the Council for the Development of Civil Society of the Republic of Croatia for the field of sports. The Council for the Development of Civil Society is an advisory body of the Government of the Republic of Croatia that works on the development of cooperation between the Government of the Republic of Croatia and civil society organizations in the Republic of Croatia in the implementation of the National Strategy for Creating an Encouraging Environment for the Development of Civil Society, the Development of Philanthropy, Social Capital, Partnerships and Inter-sectoral Cooperation. Professor Mario Kasović had independently and in co-authorship published over 70 scientific papers published in scientific journals, in full in proceedings, in the form of abstracts in conference proceedings, and over 80 professional papers published in proceedings and journals. For his scientific work entitled "Laboratory neuro-muscular test of reflex abilities of alpine skiers", he was awarded the Rector's Award in 1997. In December 2006, he received recognition for the most successful junior scientist - assistant in the academic year 2005/2006 at the Faculty of Kinesiology, University of Zagreb. He was actively involved in football, martial arts, skiing and triathlon. Since 1998, he has been active in the Diagnostic Center of the Faculty of Kinesiology in the measurement, analysis and interpretation of biomechanical testing results. He is a member of many international and domestic scientific and professional associations such as the International Society of Biomechanics (ISB), The American Senior Fitness Association (SFA), the Croatian Association of Kinesiologists, the Croatian Osteoporosis Society, the Croatian Society for Obesity Prevention, the Croatian Association of Ski Teachers and Trainers, and the Sports Recreation Society VitaSport from Zagreb. He was the President of the Croatian Triathlon Federation.

3. ACKNOWLEDGMENT

First and foremost, I would like to tank to Prof. Mario Kasović, for his unlimited support and unconditional guidance throughout this research project. I am extremely grateful for his patience and amazing ability to solve any problem. Additionally, I would like to thank to Prof. Hrvoje Sertić and Prof. Ivan Segedi for mentorship and support all through my studies. I would also like to express my gratitude to the committee members who generously provided knowledge and expertise. Finally, I would like to thank my family for their tremendous support and encouragement from day one.

4. LIST OF ABBREVIATIONS

- 3D - three-dimensional form
- CI - confidence interval
- CoP – center of pressure
- CV - coefficient of variation
- ES - effect size
- FDM - Force Distribution Measurement
- SD - standard deviation
- SPSS Inc., Chicago, IL, USA - Statistical Packages for Social Sciences software version 23
- WinFDM: software package that comes with the zebris FDM system

5. ABSTRACT

Aim: The main goal of this doctoral thesis is to determine the differences in the biomechanical gait and stance patterns under different loads of official equipment of Intervention Police Unit Officers. Three specific objectives emerge from the main goal:

1) determine the impact of carrying police equipment of different loads on the static parameters during standing.
2) determine the impact of wearing police equipment of different loads on the forces and pressures below the front, middle and rear parts of the feet during gait analysis.
3) determine the impact of wearing police equipment of different loads on the spatiotemporal characteristics of gait analysis.

Three specific objectives were established for three independent studies (**Study 1, Study 2 and Study 3**). **Study 1** aims to provide an answer to the question of whether police equipment with a higher load will significantly negatively effect on the static parameters during standing. **Study 2** aims to answer the question of whether the increased load of police equipment will lead to a significant increase in forces and pressures under the forefoot, middle and hindfoot of both feet during walking. **Study 3** aims to provide an answer to the question of whether police equipment with a higher load will significantly negatively affect the spatiotemporal parameters of gait analysis and its pattern.

Study 1

The main purpose of the study was to examine differences in foot characteristics during standing while increasing external heavy loads.

Study 1 methods: Ninety-six elite intervention male police officers were assessed in four conditions: (i) ‘no load’, (ii) ‘a 5 kg load’, (iii) ‘a 25 kg load’, and (iv) ‘a 45 kg load’. Foot characteristics while standing were assessed with Zebris pedobarographic pressure platform.

Study 1 results: Heavier loads increased 95% confidence ellipse area ($p=0.012$, $\eta2=0.028$), center of pressure path length ($p=0.010$, $\eta2=0.029$) and average velocity ($p=0.011$, $\eta2=0.029$), and length of minor ($p<0.001$, $\eta2=0.040$) and major axis ($p=0.004$, $\eta2=0.035$). No significant changes in relative ground reaction forces beneath forefoot and hindfoot regions of both feet were observed ($p>0.05$).

Study 1 conclusion: The findings suggest that spatial and temporal foot parameters may be more prone to change while carrying heavy loads, especially the center of pressure characteristics.

Study 2

The main purpose of the study was to examine whether heavier loads might have an effect on ground reaction forces and plantar pressures.

Study 2 methods: Ninety-six elite intervention police officers were recruited in this cross-sectional study. Ground reaction forces and plantar pressures beneath the different foot regions were evaluated using Zebris FDM pressure platform, while a graduate increase in load carriage was as follows: (i) 'no load', (ii) 'a 5-kg load', (iii) 'a 25-kg load' and (iv) 'a 45-kg load'.

Study 2 results: Carrying heavier loads increased ground reaction forces beneath forefoot and hindfoot regions of both feet, and midfoot region for the right foot. For plantar pressures, increases beneath the hindfoot region of both feet and midfoot region of the right foot were observed, while carrying heavier loads.

Study 2 conclusion: This study shows significant increases in both ground reaction forces and plantar pressures, especially beneath the forefoot and hindfoot regions of both feet. Since the largest forces and pressures are produced beneath the hindfoot and forefoot, future research should pay special attention to these regions and their ground absorptions, additionally preventing from muscle and joint injuries.

Study 3

The purpose of this study was to examine changes in spatial and temporal gait parameters under different loading conditions.

Study 3 methods: Ninety-six intervention police officers were recruited and evaluated. Zebris FDM pedobarographic platform was used to assess spatial and temporal gait changes while a gradual increase in load: (i) 'no load', (ii) 'a 5-kg load', (iii) 'a 25-kg load' and (iv) 'a 45-kg load'.

Study 3 results: Gradual increases in load carriage significantly increased cadence ($p = 0.024$, $\eta 2 = 0.029$), stance-phase for left ($p = 0.046$, $\eta 2 = 0.024$) and right foot ($p = 0.019$, $\eta 2 = 0.030$), and load response for left ($p = 0.044$, $\eta 2 = 0.025$) and right foot ($p = 0.033$, $\eta 2 = 0.027$), while decreases in step time for left foot ($p = 0.024$, $\eta 2 = 0.029$), and swing phase for left ($p = 0.047$, $\eta 2 = 0.024$) and right foot ($p = 0.047$, $\eta 2 = 0.024$) were observed.

Study 3 conclusion: No significant changes in spatial gait parameters occurred when carrying heavier loads. Also, findings indicated no ground reaction force gait asymmetries between the left and right foot, while walking under a progressively increased load carriage. In conclusion, increases in external loads lead to larger changes in temporal, but not in spatial foot characteristics during gait. Thus, temporal gait parameters may be more prone to changes when carrying heavy loads.

Key words: special populations; gait kinetics, police equipment; standardized load carriage; asymmetry index; effect size; foot characteristics; centre of pressure.

6. SAŽETAK

Cilj: Glavni cilj ove doktorske disertacije je utvrditi razlike u biomehaničkim obrascima hodanja i stajanja kod različitih opterećenja opremom službenika Interventne jedinice policije. Iz glavnog cilja proizlaze tri specifična cilja:

1) utvrditi utjecaj nošenja policijske opreme različitih opterećenja na statičke parametre tijekom stajanja.

2) utvrditi utjecaj nošenja policijske opreme različitih opterećenja na sile i pritiske ispod prednjeg, srednjeg i stražnjeg dijela stopala tijekom analize hoda.

3) utvrditi utjecaj nošenja policijske opreme različitih opterećenja na prostorno-vremenske karakteristike analize hoda.

Za tri neovisna istraživanja (**Studija 1, Studija 2 i Studija 3**) postavljena su tri specifična cilja. **Studija 1** ima za cilj dati odgovor na pitanje hoće li policijska oprema s većim opterećenjem značajno negativno utjecati na statičke parametre tijekom stajanja. **Studija 2** ima za cilj odgovoriti na pitanje hoće li povećano opterećenje policijske opreme dovesti do značajnog povećanja sila i pritisaka ispod prednjeg, srednjeg i stražnjeg dijela stopala oba stopala tijekom hodanja. **Studija 3** ima za cilj dati odgovor na pitanje hoće li policijska oprema s većim opterećenjem značajno negativno utjecati na prostorno-vremenske parametre analize hoda i njegov obrazac.

Studija 1

Glavni cilj studije bio je ispitati razlike u karakteristikama stopala tijekom stajanja uz povećanje vanjskog opterećenja.

Metode Studije 1: Devedeset šest elitnih interventnih policajaca muškog spola procijenjeno je u četiri razine opterečenja: (i) 'bez opterećenja', (ii) 'opterećenje od 5 kg', (iii) 'opterećenje od 25 kg' i (iv) 'opterećenje od 45 kg'. Karakteristike stopala tijekom stajanja procijenjene su pomoću Zebris pedobarografske platforme.

Rezultati Studije 1: Veća opterećenja povećala su površinu elipse s 95% pouzdanosti ($p=0,012$, $\eta2=0,028$), duljinu puta centra pritiska ($p=0,010$, $\eta2=0,029$) i prosječnu brzinu centra pritiska ($p=0,011$, $\eta2=0,029$), te duljinu sporedne ($p<0,001$, $\eta2=0,040$) i glavne osi ($p=0,004$, $\eta2=0,035$). Nisu uočene značajne promjene u relativnim silama reakcije podloge ispod prednjeg i stražnjeg dijela oba stopala ($p>0,05$).

Zaključak studije 1: Nalazi ukazuju na to da prostorni i vremenski parametri stopala mogu biti skloniji promjenama prilikom nošenja teških tereta, posebno karakteristike centra pritiska.

Studija 2

Glavni cilj studije bio je ispitati mogu li teži tereti utjecati na sile reakcije podloge i na plantarni pritisak ispod stopala.

Metode studije 2: U ovu studiju regrutirano je devedeset i šest elitnih interventnih policajaca. Sile reakcije podloge i plantarni pritisak ispod različitih područja stopala procijenjeni su pomoću Zebris FDM pedobarografske platforme, dok je postupno povećanje tereta bilo sljedeće: (i) 'bez tereta', (ii) 'teret od 5 kg', (iii) 'teret od 25 kg' i (iv) 'teret od 45 kg'.

Rezultati studije 2: Nošenje težih tereta povećalo je sile reakcije tla ispod prednjeg i stražnjeg područja stopala oba stopala te srednjeg područja stopala desnog stopala. Kod plantarnih pritisaka uočeno je povećanje ispod stražnjeg područja stopala oba stopala i srednjeg područja stopala desnog stopala, dok su se nosili teži tereti.

Zaključak studije 2: Ova studija pokazuje značajno povećanje i sila reakcije podloge i plantarnog pritiska, posebno ispod prednjeg i stražnjeg područja stopala oba stopala. Budući da se najveće sile i pritisci proizvode ispod stražnjeg i prednjeg dijela stopala, buduća istraživanja trebala bi posvetiti posebnu pozornost tim područjima i njihovoj apsorpciji s podlogom, dodatno sprječavajući ozljede mišića i zglobova.

Studija 3

Svrha ove studije bila je ispitati promjene prostornih i vremenskih parametara hoda pod različitim uvjetima opterećenja.

Metode studije 3: Regrutirano je i evaluirano devedeset i šest interventnih policajaca. Zebris FDM pedobarografska platforma korištena je za procjenu prostornih i vremenskih promjena hoda uz postupno povećanje opterećenja: (i) „bez opterećenja", (ii) „opterećenje od 5 kg", (iii) „opterećenje od 25 kg" i (iv) „opterećenje od 45 kg".

Rezultati studije 3: Postupno povećanje nošenja tereta značajno je povećalo kadencu ($p = 0,024$, $\eta 2 = 0,029$), fazu oslonca za lijevo ($p = 0,046$, $\eta 2 = 0,024$) i desno stopalo ($p = 0,019$, $\eta 2 = 0,030$) i odgovor na opterećenje za lijevo ($p = 0,044$, $\eta 2 = 0,025$) i desno stopalo ($p = 0,033$, $\eta 2 = 0,027$), dok je uočeno smanjenje vremena koraka za lijevo stopalo ($p = 0,024$, $\eta 2 = 0,029$) i faze njihanja za lijevo ($p = 0,047$, $\eta 2 = 0,024$) i desno stopalo ($p = 0,047$, $\eta 2 = 0,024$).

Zaključak studije 3: Nisu se dogodile značajne promjene u prostornim parametrima hoda pri nošenju težeg tereta. Također, nalazi nisu pokazali asimetrije hoda uzrokovane silom reakcije

podloge između lijevog i desnog stopala tijekom hodanja pod progresivno povećanim opterećenjem. Zaključno, povećanje vanjskog opterećenja dovodi do većih promjena u vremenskim, ali ne i u prostornim karakteristikama stopala tijekom hoda. Stoga, vremenski parametri hoda mogu biti skloniji promjenama pri nošenju teškog tereta.

Ključne riječi*:* posebne populacije; kinetika hoda; policijska oprema; standardizirano nošenje tereta; indeks asimetrije; veličina učinka; karakteristike stopala; centar pritiska.

7. INTRODUCTION

7.1. Context and Literary review

Carrying heavy loads represents a major part of specific military and police training and operation protocols (Brushøj et al., 2008; Knapik et al., 2004; Wills et al., 2021). To be able to perform at maximal level, special populations of military (Knapik et al., 2004; Joseph et al., 2018; Walsh & Low, 2021) and police (Dempsey et al., 2013; Joseph et al., 2018; Larsen et al., 2016; Lewinski et al., 2015; Ramstrand et al., 2016) personnel are required to execute highly demanding physical activities, including running, jumping and carrying heavy objects (Lockie et al., 2019; Marins et al., 2020). Although carrying heavy loads is necessary for combat missions and specific tasks, it has been shown that it impacts optimal locomotor functions, increases the risk of musculoskeletal injuries (Jennings et al., 2008, Wills et al., 2021), and hampers physical performance (Boffey et al., 2019; Martin et al., 2023). The history of military loads shows a trend of increasing weight over time surpassing the recommended level of 45% of body mass (Andersen et al., 2016; Orr et al., 2015). From a relative perspective, evidence shows that the load necessary for meeting tactical requirements ranges between 46% and 70% of body weight (Department of the Army, 2017). In order to compensate these heavy external loads, the bearer undergoes changes to their gait and posture (Fox et al., 2020). Numerous studies have investigated the effects of carrying an external load on physiological and biomechanical changes (Boffey et al., 2019; Faghy et al., 2022; Walsh et al., 2021). From a physiological perspective, it is expected that heavier loads increase total and active energy expenditure, heart rate, and breathing characteristics (Boffey et al., 2019) due to the greater forces applied on the musculoskeletal system (Walsh & Low, 2021). On the other hand, when it comes to the biomechanical approach, literature has consistently reported that during the loaded conditions, increases in the trunk (Attwells et al., 2006; Majumdar et al., 2010), hip (Majumdar et al., 2010; Schulze et al., 2014), knee (Majumdar et al., 2010; Rice et al., 2016) and neck (Attwells et al., 2006) flexion, ankle dorsiflexion (Majumdar et al., 2010) and hip (Attwells et al., 2006; Seay et al., 2014), knee (Attwells et al., 2006; Seay et al., 2014) and ankle (Majumdar et al., 2010; Rice et al., 2016; Seay et al., 2014) range of motion are observed, followed by decreases in trunk sway (Sessoms et al., 2019) and trunk range of motion (Morrison et al., 2019). Compared to unloaded conditions, average and peak plantar pressures increase with loaded conditions (Goffar et al., 2013; Park et al., 2013). However, there are limited data on spatial and temporal gait characteristics, as well as the differences between the sides of the body, in response to progressively heavier external loads; these have yet to be determined. Also, in previous studies little evidence has been provided regarding carrying heavy loads and foot stability during quiet stance (Kasović et al., 2022; Richmond et al., 2021; Schiffman et al., 2006; Walsh & Low, 2021). The importance of establishing changes in biomechanical foot parameters in police officers during stance comes from a high prevalence of standing and less moving activities due to sitting in a patrol car or doing administrative tasks for a long period of time, which may lead to sedentarism (Orr et al., 2020). The ability to stand still and remain postural control while carrying heavy loads is important for balance control of the body, where heavier loads tend to trigger appropriate motor responses to avoid its loss or injury/fall (Pollock et al., 2000). Even though a standing position seems relatively safe, external load placement and the magnitude of an increased postural sway and a decreased base of support (considering feet together) represents one of the main problems causing muscle strains and negative body adaptations (Zultowski & Aruin, 2008). Extreme loading conditions may lead to changes in foot placement on the ground while absorbing various shocks during heavy load carriage (Saltzman & Nawoczenski, 1995; Scott et al., 2007). Information on ground reaction forces and plantar pressures during load carriage may be relevant to describe the mechanisms of gait and to provide the magnitude of impact forces acting on the foot (Birrell et al., 2007). Carrying heavy loads may alternatively lead to musculoskeletal and neurological injuries caused by greater forces being distributed on the foot (Orr et al., 2015; Orr et al., 2021). A prolonged load carriage can lead to fatigue (Fallowfield et al., 2012), with longitudinal studies suggesting that knee, ankle and foot are the most common body sites of musculoskeletal pain (Orr et al., 2015; Reynolds et al., 1999). Most of the studies of the effects of carrying heavy loads on ground reaction forces (Dar et al., 2023; Goffar et al., 2013; Lenton et al., 2019; Majumdar et al., 2013; Sessoms et al., 2020; Tilbury-Davis & Hooper, 1999; Wang et al., 2023) and plantar pressures (Goffar et al., 2013; Park et al., 2013) has been conducted among military personnel. A recent study conducted among elite special police officers has shown significant changes in both ground reaction forces and plantar pressures beneath different foot regions while carrying heavy loads, pointing out that special population of police officers may be more prone to kinetic gait changes, compared to military active-duty solders (Kasović et al., 2023). In specific, a study by Kasović et al. (2023) showed gradual increases in ground reaction forces and plantar pressures under forefoot, midfoot and hindfoot regions of both feet following heavier load carriage, while temporal gait parameters, including walking speed, remained unchanged. This would imply that increases in force beneath both feet might be predominantly due to the static effect of the load rather than temporal changes of the system (Birrell et al., 2007). Carrying excessive load can impact the biomechanics of human locomotion (Boffey et al., 2018; Liew et al., 2016). During carriage, the extra load requires gait compensation to minimize decrements in maximal performance (Baggaley et al., 2020; Liew et al., 2016; Orr et al., 2014). Most parameters associated with gait include spatiotemporal data, kinematics, ground reaction forces, and electromyography (Walsh & Low, 2021). Past findings have shown inconclusive results, where the added external mass can impact spatiotemporal gait parameters (Boffey et al., 2018; Liew et al., 2016), or have no proven effects (Walsh & Low, 2021). For example, previous systematic reviews have shown that external weight may lead to a reduced stride length and an increased cadence during walking (Boffey et al., 2018; Liew et al., 2016). However, the most recent systematic review has demonstrated that load carriage had no significant effect on any of the spatiotemporal gait parameters, including walking speed, step or stride length, cadence, step width, and double or single support time (Walsh & Low, 2021). During bipedal movements, it is normal to observe a certain level of asymmetry. The term "asymmetry" is one of the key factors and a starting point in defining optimal ergonomic efficiency and load positioning on the body. Thus, it is not surprising that it has gained significant attention over the last two decades (Lanshammar & Ribom, 2011; Seeley et al., 2008; Shi et al., 2015). Indeed, efforts have been made to determine an optimal level of asymmetry for certain physical performance parameters, indicating that a 15% difference between the sides of the body represents an upper threshold (Lanshammar & Ribom, 2011). However, these patterns have rarely been observed in the lower extremities, where the literature indicates an increase of up to 50% when carrying heavier loads (Seeley et al., 2008). Most studies have attempted to examine the effects of uneven load carriage on gait biomechanics (DeVita et al., 1991; Majumdar et al., 2013; Ozgül et al., 2012; Park et al., 2018; Shi et al., 2015; Zhang et al., 2010). When carrying an asymmetrical load, previous kinematic analyses have shown that the body naturally increases extensor moments in the hip and knee of the unloaded leg (DeVita et al., 1991). While examining joint movement during walking, little is known about the relationship between load carriage and spatiotemporal gait asymmetries (Zhang et al., 2010). The available studies on this topic have shown an increase in gait asymmetry in the ground reaction forces in the medio-lateral direction when heavier loads (up to roughly 20% of the body's weight) are applied (Zhang et al., 2010). Most recently, a studies by Kasović et al. (2024) and Štefan et al. (2024, 2025) indicated that a 3.5 kg load significantly increased asymmetries in the gait cycle, particularly during the stance, load response, single-limb support, pre-swing, and swing phases and in the step time, compared to the no-load condition in a large sample of police recruits. However, the limitation of the previously mentioned studies is its exclusive focus on a 3.5 kg load, while the effects of heavier loads on spatiotemporal gait asymmetries remain unexamined.

the potential increases in gait asymmetry may result in the even greater eversion and external rotation of the foot, decreases in the step and stride length, and increases in the step and stride time (Kasović et al., 2020), which could lead to injuries and stress fractures (Sharm et al., 2014; Teyhen et al., 2020; Yavnai et al., 2021). The main purpose of the study was to examine whether carrying progressively heavier loads (‘no load’, ‘a 5 kg load’, ‘a 25 kg load’, and ‘a 45 kg load’) had effects on the biomechanical patterns of walking and standing of officers of the Police Intervention Unit.

7.2. Lists of tables

Study one

Table 1. Basic descriptive statistics and changes in static foot parameters under the different loading conditions in intervention police officers

Study two

Table 1. Changes in ground reaction forces and plantar pressures under the different loading conditions.

Table 2. Summary of an increase, decrease or no effect of load carriage on ground reaction forces and plantar pressures for both feet.

Study three (paper one)

Table 1. Changes in spatial gait parameters under the different loading conditions.

Table 2. Changes in temporal gait parameters under the different loading conditions.

Study three (paper two)

Table 1. Changes in the spatial gait parameters under the different loading conditions.

Table 2. Changes in the temporal gait parameters under the different loading conditions.

Table 3. Changes in the ground reaction force asymmetries under the different loading conditions.

7.3. Research aims and questions

The main goal of this doctoral thesis is to determine the differences in the biomechanical patterns of walking and standing under different loads with the equipment of officers of the Police Intervention Unit.

Regarding the main goal, the following sub-goals were generated:

1. to determine the impact of carrying police equipment of different loads on the static parameters during standing.
2. to determine the impact of wearing police equipment of different loads on the forces and pressures below the front, middle and rear parts of the feet during gait analysis.
3. to determine the impact of wearing police equipment of different loads on the spatiotemporal characteristics of gait analysis.

The main research hypotheses are:

1. H1: Police equipment with the heavier loads will have a significant negative impact on the static parameters during standing.
2. H2: Increased loads on police equipment will lead to a significant increase in forces and pressures below the front, middle and rear of both feet during walking.
3. H3: Police equipment with the heavier loads will have a significant negative impact on the spatiotemporal parameters of gait analysis and its pattern.

7.4. List of research studies

Three specific objectives were established for three independent studies. All studies were published in peer-reviewed international journals. The studies are listed according to the date of submission:

1. Kasović, M., **Rožac, D.**, Štefan, A., Štefan, L., & Milković, S. (2024). Effects of Different Load Carriage on Spatiotemporal Gait Parameters in Elite Intervention Police Officers. *Applied Sciences, 14*(1), 278. https://doi.org/10.3390/app140102781.
2. Kasović, M., **Rožac, D.**, Štefan A., Vespalec, T., & Štefan, L., (2024). Does carrying heavy loads impact ground reaction forces and plantar pressures in intervention police officers? *PeerJ ,12,* e16912 https://doi.org/10.7717/peerj.16912
3. **Rožac, D.**, Kasović, M. & Štefan, A. (2024). Impact of carrying heavy loads on postural sway and relative ground reaction forces during quiet stance in intervention police officers. *Kinesiology, 56* (1), 127-134. https://doi.org/10.26582/k.56.1.7
4. **Rožac, D.**, Kasović, M., & Knjaz, D. (2024). Spatiotemporal Gait Asymmetries Remain Unaffected by Increased Load Carriage in Professional Intervention Police Officers. *Bioengineering*, *11*(11), 1140. https://doi.org/10.3390/bioengineering11111140

7.5. Thesis outline

Chapter 1 defines the thesis research problem. This chapter provides background information regarding the thesis and an overview of literature review that is relevant for this research.

Chapter 2 provides a comprehensive overview of how the study was carried out, including the research design, data collection techniques, sampling methods, and data analysis procedures.

Chapter 3 presents the research studies included in this thesis. Study 1 aims to provide an answer to the question of whether police equipment with a higher load will significantly negatively effect on the static parameters during standing. Study 2 aims to answer the question of whether the increased load of police equipment will lead to a significant increase in forces and pressures under the forefoot, middle and hindfoot of both feet during walking. Study 3 aims to provide an answer to the question of whether police equipment with a higher load will significantly negatively affect the spatiotemporal parameters of gait analysis and its pattern.

Chapter 4 makes a conclusion to the dissertation by summarizing each of the presented papers. We present how this research contributes to existing scientific knowledge in both the fields of kinesiology and safety studies. Finally, we identify the strengths and limitations of the study and present recommendations for future research.

8. RESEARCH METODOLOGY

8.1. Study population

In this cross-sectional study, we recruited male officers of the Police Intervention Unit of the Zagreb Police Department. By using the G*Power statistical calculator to calculate the sample size and setting a statistical power of 0.80, a p-value of <0.05, and detection of large effect size (0.40), a sufficient number of subjects to participate in the study would be N = 80. Considering the potential dispersion of the sample during the implementation of the study, the sample was increased by 20% (N = 96). To be included in the study, all participants in the research were employees of the Police Intervention Unit for a minimum period of three years. Before and during the test, all participants needed to be without any acute/chronic diseases and injuries that would affect the test results or force them to drop out of the study. The research was conducted anonymously and in accordance with the Helsinki Declaration (World Medical Association, 2013). Before the study, a written informed consent was signed by all participants. This study was approved by the Ethical Committee of the Faculty of Kinesiology and the Police Intervention Department under the Ministry of Internal Affairs of the Republic of Croatia (Ethical code: 511-01-128-23-1).

8.2. Loading Conditions

For each loading condition, participants wore four types of loads proposed by the Ministry of Internal Affairs for intervention police officers: (1) ‘no load’, which only included their own body weight (2) a 5-kg load referring as ‘load 1’, which consisted of a belt with a loaded handgun magazine with an additional full handgun magazine and a standard set of handcuffs, (3) a 25-kg load referring as ‘load 2’, which represented ‘load 1’ + a helmet, a ballistic vest and a baton, and (4) a 45-kg load referring as ‘load 3’, which was a cumulative load of ‘no load’ + ‘load 1’ + ‘load 2’ with additional protection equipment for extremities and accompanied by a protective gas mask (Kasović et al., 2022). Previous findings have suggested that the order of the load being carried should be randomized, for the purpose of reducing a learning effect (Kasović et al., 2022). It should be noted that each load condition served for specific tasks and duties inside or outside the field for intervention police officers and these loads were chosen due to the highest amount of time being carried during working hours.

8.3. Study variables

Study 1

In this research static foot parameters were measured. The static variables that used for the analysis are: (1) 95% confidence ellipse area (mm2), (2) CoP path length (mm), (3) CoP average velocity (mm/s), (4) length of the minor axis, (5) length of the major axis (mm), (6) deviation X, (7) deviation Y, and (8) the angle between Y and the major axis (°). For ground reaction forces, the software generated the data for the relative forces distributed under the forefoot and hindfoot regions of the foot, as well as for the total foot (%). Of note, the vertical component of the ground reaction forces was collected and analyzed as well.

Study 2

Ground reaction parameters recorded from the software were forces and pressures under individual regions of the foot and gait parameters. The kinetic parameters of the gait analysis are: 1) maximum forces under the front, middle and rear parts of both feet expressed in newtons (N), and 2) maximum pressures under the front, middle and rear parts of both feet expressed in newtons per surface area (N/cm2). For the dynamic measurements, the load distribution beneath the forefoot, midfoot and hindfoot regions of the feet is recorded during walking over the pressure platform.

Study 3

Spatial gait analysis parameters that we analyzed were: 1) foot rotation (external/internal), 2) step length (length between the heel of the right foot and the left foot, when taking a step), 3) length of two steps (length from the heel of the right foot to the heel of the right foot for two steps), and 4) step width (transverse width between both feet). The time parameters of gait analysis are: 1) step time (time required for a step), 2) two-step time (time required to make a two-step), 3) cadence (number of steps per minute), and 4) walking speed expressed in meters per second (m/s). In addition, further temporal parameters recoded as % of the gait cycle for both feet were divided into two phases: (1) stance phase described by load response, mid stance, and pre-swing, and (2) swing phase. Finally, a double stance phase was generated. Of note, foot rotation, step length, length of gait line from the first to the final contact of the foot with the ground, a single support line, step time, and the % of gait cycle were calculated for both left and right foot. The gait asymmetry for each parameter was calculated using the formula (x_{right} –

$x_{left})/0.5 \times (x_{right} + x_{left})*100\%$, where “x” represents the numerical value of each parameter for the left and right sides of the body.

8.4. Testing Procedures

Study 1

At the meter's signal, the subject stood on the pedobarographic platform (ZEBRIS company, FDM; GmbH, Munich, Germany; number of sensors: 11,264; sampling rate: 100 Hz; sensor area: 149 cm × 54.2 cm) in his natural position (stride position, arms relaxed by the body, gaze directed forward, normal breathing), and kept the upright body position for 15 seconds. After 15 seconds and at the meter's signal, the subject moved from the platform, and the Zebris software package (WinFDM) analyzed the data. Each respondent tested four times; the first attempt tested without equipment and after that with different levels of equipment. The mass of police equipment categorized into 4 levels. The first level of equipment was characterized by wearing a police uniform without a belt, i.e., without a load. The second level was characterized by carrying the basic equipment, which includes a belt, a gun with a magazine, an additional magazine, and police handcuffs. The third level of equipment was an addition to the second level in terms of wearing a specially designed police helmet, ballistic vest, and multi-purpose baton (tonfa). The last fourth level of equipment included the third level of equipment with additional protection for the lower extremities and a protective gas mask.

Study 2

To be able to calculate ground reaction forces and plantar pressures, we used a pedobarographic platform (ZEBRIS company, FDM; GmbH, Munich, Germany; number of sensors: 11,264; sampling rate: 100 Hz; sensor area: 149 cm × 54.2 cm), a simple and easy-to-administrate tool to investigate gait characteristics and followed the testing procedure in similar populations (Kasović et al., 2023; Kasović et al., 2024). Specifically, each participant walked barefoot over a platform for eight consecutive times at a self-selected walking speed with a different external load. Before and after the platform, two custom-made wooden platforms were placed, in order to establish normal gait. When the measurer gave the signal, the participant started to walk over the platform and when the end of a walkway was reached, the participant stopped, turned around and started walking towards the starting point). Each respondent tested four times; the first attempt tested without equipment and after that with different levels of equipment. The mass of police equipment categorized into 4 levels. The first level of equipment was characterized by wearing a police uniform without a belt, i.e., without a load. The second level was characterized by carrying the basic equipment, which includes a belt, a gun with a magazine, an additional magazine, and police handcuffs. The third level of equipment was an addition to the second level in terms of wearing a specially designed police helmet, ballistic vest, and multi-purpose baton (tonfa). The last fourth level of equipment included the third level of equipment with additional protection for the lower extremities and a protective gas mask.

Study 3

We used a pedobarographic platform (ZEBRIS company, FDM; GmbH, Munich, Germany; number of sensors: 11,264; sampling rate: 100 Hz; sensor area: 149 cm × 54.2 cm) to assess spatiotemporal gait parameters. Each participant walked over the pedobarographic platform with an additional 4.5 m custom-designed dense material platform put before and after the testing area. To be able to complete the task, the participants walked a 4.5 m platform after which they stepped and walked over the pressure platform and continued to walk across the next 4.5 m platform to the end of a walkway. When they reached the end, they rotated 180◦ and continued to walk over the platform seven more times (eight trials in total). The resting period between each load was approximately 3 min or when the heart rate was below 100 beats per min (Sey et al., 2014). Each respondent tested four times; the first attempt tested without equipment and after that with different levels of equipment. The mass of police equipment categorized into 4 levels. The first level of equipment was characterized by wearing a police uniform without a belt, i.e., without a load. The second level was characterized by carrying the basic equipment, which includes a belt, a gun with a magazine, an additional magazine, and police handcuffs. The third level of equipment was an addition to the second level in terms of wearing a specially designed police helmet, ballistic vest, and multi-purpose baton (tonfa). The last fourth level of equipment included the third level of equipment with additional protection for the lower extremities and a protective gas mask.

8.5. Data processing

The Kolmogorov–Smirnov test was used to assess the normality of the distribution. For normally distributed variables, basic descriptive statistics are presented as mean and standard deviation (SD). For not normally distributed variables, median and interquartile range (25th–75th) were applied.

Pearson correlation coefficient was used to assess the level of connection between sociodemographic characteristics and changes under each load condition, to omit potential mediation. One-way repeated-measures ANOVA was used to test the effects of load configuration (‘no load’, ‘load 1’, ‘load 2’ and ‘load 3’). Where significant differences between load configurations were observed, a modified Bonferroni procedure was used. All statistical analyses were performed using SPSS v23.0 software (IBM, Armonk, NY, USA) with an alpha level set a priori at $p<.05$ to denote statistical significance.

9. ORIGINAL STUDIES

9.1. Research study one

Article title

Impact of carrying heavy loads on postural sway and relative ground reaction forces during quiet stance in intervention police officers

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9.1.1. Abstract

Introduction

Although carrying heavy loads impacts gait characteristics in military personnel, less studies have examined whether a gradually load increase affects foot parameters during quiet standing in the different population of intervention police officers. Therefore, the main purpose of the study was to examine differences in postural sway and ground reaction force characteristics during a quiet stance while carrying progressively heavier equipment.

Materials and Methods

Ninety-six elite intervention male police officers (age 38.2 ± 10.4 years, body height 179.2 ± 12.4 cm, body mass (86.4 ± 11.3 kg), were assessed under four conditions: (1) 'no load', (2) 'a 5 kg load', (3) 'a 25 kg load', and (4) 'a 45 kg load'. Foot characteristics during standing were assessed with the Zebris pedobarographic pressure platform. Measured parameters were: (1) 95% confidence ellipse area (mm2), (2) CoP path length (mm), (3) CoP average velocity (mm/s), (4) length of the minor axis, (5) length of the major axis (mm), (6) deviation X, (7) deviation Y, and (8) the angle between Y and the major axis (°). For ground reaction forces, the software generated the data for the relative forces distributed under the forefoot and hindfoot regions of the foot, as well as for the total foot (%). The vertical component of the ground reaction forces was collected and analyzed as well.

Results

Heavier loads increased 95% confidence ellipse area ($p=.012$, $\eta 2=0.028$), the center of pressure path length ($p=.010$, $\eta 2=0.029$) and average velocity ($p=.011$, $\eta 2=0.029$), and length of the minor ($p<.001$, $\eta 2=0.040$) and major axis ($p=.004$, $\eta 2=0.035$). No significant changes in relative ground reaction forces beneath the forefoot and hindfoot regions of both feet were observed ($p>.05$).

Conclusion

The findings of the study showed that with gradually increased external loads, the center of pressure path length and velocity increased along with the major and minor axes, while changes in ground reaction forces beneath the different foot regions were not impacted by the load. Therefore, the findings suggest that spatial and temporal foot parameters may be more prone to change while carrying heavy loads, especially the center of pressure characteristics.

9.1.3. Introduction

Carrying excessive load represents a major part of both training and operation protocols in special population of military and police personnel (Brushøj et al., 2008; Knapik et al., 2004; Wills et al., 2021). Although such load is important for combat missions and specific tasks, it has been shown that it impacts optimal locomotor functions, increases the risk of lower limb injury (Wills et al., 2021), and hampers physical performance (Boffey et al., 2019; Martin et al., 2023). Unfortunately, a negative trend in load weight has been observed, surpassing the recommended level of 45% of body mass (Andersen et al., 2016; Orr et al., 2015). From a relative perspective, evidence shows that the load necessary for meeting tactical requirements ranges between 46% and 70% of body weight (Department of the Army, 2017). When carrying heavy loads, an individual often tends to compensate, causing changes in gait and posture characteristics (Fox et al., 2020). From a biomechanical point of view, heavy equipment during walking may impact balance, movement and overall postural stability, leading to greater torques in hip and trunk areas, which can cause alterations in body control (Heller et al., 2009). However, little evidence has been provided regarding carrying heavy loads and foot stability during quiet stance (Kasović et al., 2022; Richmond et al., 2021; Schiffman et al., 2006; Walsh & Low, 2021;). In the process of quantifying the effects of load carriage in a stance position, first changed activity of antigravity muscles of the trunk should be observed, then, the postural sway as well as spatial- and temporal-related foot parameters, which may lead to higher incidence of injuries (Kroemer & Grandjean, 1997). The importance of establishing changes in biomechanical foot parameters in police officers during stance comes from a high prevalence of standing and less moving activities due to sitting in a patrol car or doing administrative tasks for a long period of time, which may lead to sedentarism (Orr et al., 2020). The ability to stand still and remain postural control while carrying heavy loads is important for balance control of the body, where heavier loads tend to trigger appropriate motor responses to avoid its loss or injury/fall (Pollock et al., 2000). Even though a standing position seems relatively safe, external load placement and the magnitude of an increased postural sway and a decreased base of support (considering feet together) represents one of the main problems causing muscle strains and negative body adaptations (Zultowski & Aruin, 2008). Although external load is important for survival, it may increase the risk of injury due to requirements to repetitively generate muscular force, causing whole-body fatigue and increasing energy costs connected to prolonged load carriage (Fallowfield et al., 2012; Tahmasebiet al., 2015). Indeed, evidence suggests that deviations of the center of pressure can predict future risk of injury and postural instability through shorter intervals in mediolateral axis (Blacker et al., 2010), causing ligamentous damage, especially in the lower extremities (Knapik et al., 2004). Both cross-sectional (Reynolds et al., 1999) and longitudinal (Orr et al., 2015; Orr et al, 2017) studies have shown that different load distribution may have even larger negative effects and can increase the level of asymmetry. Studies conducted during quiet standing have concluded that loads with a predominant mass of >40% of body weight increase pressure velocity and the contact area between the foot and the ground, directly affecting ground reaction forces beneath different foot regions (Kasović et al., 2022; Richmond, et al., 2021; Schiffman et al., 2006; Strube et al., 2017; Tahmasebi et al., 2015; Walsh & Low, 2021). Although carrying heavy loads has been mainly observed in military personnel (Walsh & Low, 2021), studies have shown that other special populations, like police officers, may be more prone to biomechanical foot changes during quiet stance (Kasović et al., 2022). Intervention police officers are required to perform their everyday tasks at a maximal level (Zwingmann et al., 2021). Their primary role includes intervening against crime, and they are engaged in high-risk situations that often exceed the capabilities of general police (Zwingmann et al., 2021). The most common everyday tasks are related to personal or community protection of high risk, including sports matches and events, rural operations of controlling an illegal border crossing by immigrants, or even participating in counterterrorism operations (Irving et al., 2019). To be able to perform at high level, intervention police officers often need to carry external loads that exceed recommended levels of 45% of body mass (Department of the Army, 2017). Since intervention police officers may carry even heavier load than military personnel and engage in more high-risk situations (Zwingmann et al., 2021), it is necessary to examine changes in biomechanical foot parameters during quiet standing under heavy load conditions. Therefore, the main purpose of the study was to examine whether carrying progressively heavier loads ('no load', 'a 5 kg load', 'a 25 kg load', and 'a 45 kg load') had effects on postural sway and relative ground reaction forces during quiet stance in intervention police officers. We hypothesized that officers would exhibit greater biomechanical foot changes and impaired balance under heavier loads compared to the 'no load' condition.

9.1.4. Materials and Methods

Study participants

In this cross-sectional study, male officers of the Police Intervention Unit of the Zagreb Police Department were recruited. Out of 280 registered intervention police officers, we were able to recruit just 96 of them due to different field-based and administrative tasks other individuals were participating in. G*Power statistical calculator was used to calculate the effect size using partial eta squared and the one-way repeated-measures ANOVA to compare the effects of load configuration, with a p-value of <.05, achieved power of 0.80, a total recruited sample size of N = 80 (out of 280 participants), four measurements, correlation among repeated measures to be set at r = 0.50, and a nonsphericity correction index of 1, the achieved effect size with the aforementioned number of participants was f = 0.25. Considering the potential dispersion of the sample during the study, the initial sample size of 80 participants was increased by 20%, leading to the final sample of 96 participants. All participants in the research were employees of the Zagreb Police Intervention Unit for at least three years. All participants recruited for this study were men. Sociodemographic characteristics included age (mean ± SD; 38.2 ± 10.4 years), body height (179.2 ± 12.4 cm), body mass (86.4 ± 11.3 kg), body mass index (26.9 ± 3.8 kg/m2), and waist circumference (93.5 ± 12.6 cm). The mean age of serving as an intervention police officer was 10.3 ± 3.3 years. Out of 96 participants, seven were underweight (7.3%), 65 had normal weight (67.7%), 20 were overweight (20.8%), and four were obese (4.2%). All participants signed a written informed consent to participate and stated that they did not have any acute/chronic diseases or injuries that would affect the test results or force them to drop out from the study. The research was conducted anonymously and in accordance with the Helsinki Declaration (World Medical Association, 2013). This study was approved by the Ethical Committee of the Faculty of Kinesiology and the Police Intervention Department under the Ministry of Internal Affairs of the Republic of Croatia (Ethical code: 511-01-128-23-1).

Load equipment

During testing, each participant walked over a platform and carried four types of loads proposed by the Ministry of Internal Affairs for intervention police officers: (1) body weight only ('no load'), (2) a 5-kg load ('load 1', a belt with a pistol loaded with a full handgun's magazine, an additional full handgun's magazine and handcuffs), (3) a 25-kg load ('load 2'; 'load 1' upgraded by a helmet, a ballistic vest and a multipurpose baton), and (4) a 45-kg load ('load 3'; 'load 2' upgraded by the additional protection for the lower extremities and a protective gas mask). The order of the load carrying was randomized by the randomization software to reduce the impact of a learning effect (Kasović et al., 2022). All the participants wore the same standardized equipment for each load condition. Note, each participant wore the handgun on the dominant side of the body, which was predominantly the right side (93% of all the participants).

Static foot parameters

Measurements were conducted at the same time in the evening hours and at the same place. All respondents were familiar with the measurement protocol before the measurements. First, the anthropometric characteristics of the examinees were measured, including body height and body mass. Ground reaction forces (absolute in N and relative in %) were measured. Each participant stepped barefoot on the Zebris medical platform for the measuring of pedobarographic plantar characteristics (type FDM 1.5). The Zebris platform uses 11.264 micro sensors, arranged across the walking area, with a frequency of 300 Hz. It has been used as a diagnostic device for supporting several modes of operation, including static analysis while a participant is standing quietly (Gregory & Robertson, 2017). The Zebris platform was connected via USB cable to an external unit (laptop). The data was gathered in real time using WinFDM software for the extraction and calculation. Measurement values could be additionally exported in the form of text, picture, and video, while simultaneously comparing the data from both feet. The capacity sensor technology was based on the automatic calibration of every single sensor integrated into the platform. The task was to stand on the platform and maintain a calm position, with the arms relaxed close to the body and looking straight forward. After 15 seconds of measurement, the following parameters were generated: (1) 95% confidence ellipse area (mm2), (2) CoP path length (mm), (3) CoP average velocity (mm/s), (4) length of the minor axis, (5) length of the major axis (mm), (6) deviation X, (7) deviation Y, and (8) the angle between Y and the major axis (°). For ground reaction forces, the software generated the data for the relative forces distributed under the forefoot and hindfoot regions of the foot, as well as for the total foot (%). Of note, the vertical component of the ground reaction forces was collected and analyzed as well.

Statistical analysis

Basic descriptive statistics are presented as mean and standard deviation (SD). The Kolmogorov-Smirnov test was used to assess the normality of the distribution. Pearson correlation coefficient was used to assess the level of connection between sociodemographic characteristics and changes under each load condition, to omit potential mediation. One-way repeated-measures ANOVA was used to test the effects of load configuration ('no load', 'load 1', 'load 2' and 'load 3'). Where significant differences between load configurations were observed, a modified Bonferroni procedure was used. All statistical analyses were performed using SPSS v23.0 software (IBM, Armonk, NY, USA) with an alpha level set a priori at $p<.05$ to denote statistical significance.

9.1.5. Results

Of note, sociodemographic characteristics of the study participants were not significantly correlated to changes in stance characteristics following different load conditions ($r = 0.03 – 0.21$, $p>.05$), omitting potential mediation between a specific load condition and spatiotemporal stance changes. Changes in static foot parameters under the different loading conditions are presented in Table 1. Significant main effects were observed for confidence ellipse area, center of pressure path length and average velocity, length of the minor and major axes and deviation X.

Table 1. Basic descriptive statistics and changes in static foot parameters under the different loading conditions in intervention police officers

Study variables	'No load'	'Load 1'	'Load 2'	'Load 3'	Main effect	
Static parameters	**Median (25th-75th)**	**Median (25th-75th)**	**Median (25th-75th)**	**Median (25th-75th)**	***F* (p-value*)***	**η2**
Confidence ellipse area (mm^2)	107.5 (68-183.5)[c]	124.5 (77.5-253.8)	144.5 (98.3-215.8)	188.5 (98.8-297.5)	**3.672 (0.012)**	**0.028**
Center of pressure path length (mm)	76.0 (63.3-91.8)[c]	81.5 (63.0-107.8)	82.0 (70.0-101.0)	91.0 (71.3-114.5)	**3.801 (0.010)**	**0.029**
Center of pressure average velocity (mm/s)	8.0 (6.0-9.0)[c]	8.0 (6.0-11.0)	8.0 (7.0-11.0)	9.0 (7.0-11.0)	**3.778 (0.011)**	**0.029**
Length of the minor axis (mm)	7.4 (5.1-9.6)[a,c]	8.3 (6.2-12.2)	8.6 (6.3-11.3)	9.1 (7.2-12.1)	**5.259 (<0.001)**	**0.040**
Length of the major axis (mm)	18.6 (14.8-24.5)[c]	22.1 (16.1-27.7)	21.1 (17.6-27.0)	23.9 (18.8-32.3)	**4.550 (0.004)**	**0.035**
Angle btween Y and the major axis (°)*	75.0 (16.0)	75.7 (14.5)	74.9 (15.4)	72.1 (20.0)	0.868 (0.458)	0.007
Deviation X (mm)	18.9 (8.4-31.0)[a]	13.9 (3.8-23.5)	17.7 (9.5-27.3)	18.4 (8.8-27.6)	**2.698 (0.046)**	**0.021**
Deviation Y (mm)	4.8 (-4.0-10.4)	6.9 (-2.2-15.2)	9.1 (-0.7-19.4)	9.3 (-2.2-17.1)	0.141 (0.935)	0.001
Relative average forceleft forefoot (%)	54.1 (5.7)	55.0 (6.6)	55.5 (6.8)	55.5 (8.3)	0.884 (0.449)	0.007
Relative average forceleft hindfoot (%)	45.9 (5.7)	45.1 (6.6)	44.5 (6.8)	44.5 (8.3)	0.898 (0.442)	0.007
Relative average forceleft total (%)	44.9 (9.6)	46.3 (9.1)	44.1 (8.6)	44.3 (7.3)	1.233 (0.297)	0.010
Relative average forceright forefoot (%)	51.2 (7.9)	51.4 (10.1)	50.8 (8.7)	51.0 (7.7)	0.079 (0.972)	0.001
Relative average forceright hindfoot (%)	48.8 (7.9)	48.0 (8.7)	49.2 (8.7)	49.0 (7.7)	0.354 (0.787)	0.003
Relative average forceright total (%)	55.2 (9.6)	53.7 (9.1)	56.0 (8.4)	55.7 (7.3)	1.318 (0.268)	0.010

Note. [a] denotes significant differences between 'no load' and 'load 1'; [b] denotes significant differences between 'no load' and 'load 2'; [c] denotes significant differences between 'no load' and 'load 3'; [d] denotes significant differences between 'load 1' and 'load 2'; [e] denotes significant differences between 'load 1' and 'load 3'; [f] denotes significant differences between 'load 2' and 'load 3'. p<.05.

A Bonferroni post-hoc analyses revealed significant differences between 'no load' and 'load 3'. Specifically, carrying 'load 3' produced significantly larger effects on the aforementioned static foot parameters compared to the 'no load' condition. Interestingly, when carrying 'load 1', the value in deviation X axis significantly decreased compared to the 'no load' condition. Insignificant main effects in other static foot parameters were observed, pointing out that heavier equipment did not significantly impact deviation Y and relative forces under forefoot and hindfoot regions of both feet ($p>.05$).

9.1.6. Discussion

The main purpose of the study was to examine whether heavier equipment led to changes in postural sway and relative ground reaction forces during quiet stance in intervention police officers. The main findings of the study are: (1) with the increased mass, increases in the center of pressure path length, average velocity and lengths of the minor and major axes gradually increased, and (2) no significant changes in relative ground reaction forces beneath the forefoot and hindfoot regions of the foot were observed irrespective of heavier loads. Based on the aforementioned findings, the hypothesis of spatiotemporal and kinetic static foot changes when carrying different load could be partially confirmed, where spatiotemporal parameters led to significant changes, while relative ground reaction forces remained unchanged. To the best of authors' knowledge, this is one of the first studies that examined whether heavier loads might impact static foot parameters in intervention police officers. Previous evidence has confirmed that heavier loads may impact several foot characteristics during quiet stance, including increases in mean postural sway during a double stance, the center of pressure path length, average velocity and lengths of the minor and major axes with a decrease in the angle between Y and the major axis (Strube et al., 2017; Walsh & Low, 2021). Specifically, a study by Strube et al. (2017) showed that mean postural sway velocity during a double leg stance increased from 0.27°·s-1 to 0.34°·s-1 when carrying 'a 16.0-kg load' and to 0.52°·s-1 under the '20.5-kg load', indicating a linear velocity increase while carrying heavier loads. However, the pattern of our findings clearly indicated significant differences only between 'no load' and 'load 1'/'load 3', while no other differences were observed. Unfortunately, we performed the experiment with a relatively small sample of intervention police officers; a greater sample might have led to a greater heterogeneity between the study participants in terms of their different characteristics, the duration of the load application, or the sensitivity of the postural sway measurement techniques employed. The nature of Zebris platform applied in this study was focused on vertical component (axis) of collecting the data, while antero-posterior or medio-lateral directions could not be determined. Although limited data had a significant impact on generalizability of the findings, uneven effects of carrying heavier loads on postural sway may be explained by the fact that experienced intervention police officers participated in the study, whose body adaptations were more adequate compared to new recruits. This is in line with previous evidence, where heavy load carried by young adults led to a decrease in postural stability with significant effects on the center of pressure sway area and the center of pressure anterior-posterior excursion (Martin et al., 2023). Interestingly, studies have shown that 'a 16-kg load' may represent a significant cut-off point and result in substantial alterations in postural control (Heller et al., 2009; Schiffman et al., 2006; Strube et al., 2017), compared to lighter loads, which is not in line with our findings. The post-hoc analysis showed that compared to the 'no load', 'a 45-kg load' led to significant changes in postural sway, mainly in the center of pressure. Of many potential factors influencing body posture, muscle activation plays an important role in maintaining an upright body posture and controls the integration of sensory systems during quiet standing (Kodithuwakku Arachchige et al., 2020). Also, load placement relative to the body's center of mass was found to influence the amount of postural sway (Rugelj & Sevšek, 2011); when the load was placed above the center of mass, the sway parameters increased (Qu & Nussbaum, 2009). Although we were unable to test different load distribution and its impact on foot characteristics during quiet standing, studies have shown that load re-distribution towards the hips is an essential part of reducing metabolic costs and increasing contributions of hip muscles to forward progression (Jones et al., 2010; Kavounoudias et al., 1999). Heavier loads lead to greater foot changes and body sway during standing, which directly disrupt the body's center of mass to shift from a stable to the boundaries of the base of support, expecting a loss of balance in medio-lateral and anterior-posterior directions essential to maintain an upright stance by using the ankle and the hip compensation movements (Schiffman et al., 2006). Losing postural stability is based on a stable system of a kinetic chain between gravity, the base of support and the center of mass. When an upright neutral position is impacted by external load, the resulting body motion is counterbalanced by one of the strategies which increases postural sway. Besides biomechanical, the physiological effects of carrying heavy loads often result in larger heart rate frequency, respiratory changes and proprioceptive systems (Horak & Nashner, 1986). Along with postural changes, we observed no effects of carrying load on relative ground reaction forces, which is not in line with previous findings (Birrell et al., 2007; Kasović et al., 2022; Walsh & Low, 2021). A study by Walsh & Low (2021) concluded that ground reaction forces linearly increased with heavier load. On the other hand, observing no changes in ground reaction forces was shown in a study by Goffar et al. (2013). The discrepancy in the findings may be due to different measuring modes and techniques, where the majority of the studies have been conducted in dynamic conditions, while we based the findings in static conditions. Again, more experienced officers may better compensate for heavy loads, and since the load was placed near the body in this study, it is speculated that load placement away from the body may have produced different changes in ground reaction forces. Also, the software used to generate data on calculated ground reaction forces relative to body weight, which is one of the novelties of this study. Although a quarter of the participants were overweight or obese, the interaction between body mass index and changes in postural sway or ground reaction forces were nonsignificant, meaning that both absolute and relative values of body mass index in our sample were homogenous and other risk factors should be considered when establishing the effect of load carriage on static foot parameters.

9.1.7. Conclusions

In general, carrying heavy loads is an essential part of special populations' tasks. Along with its benefits, a negative trend of an increase in heavy loads led to a certain delay in the feedback of the ability to maintain an upright control and posture. However, body movement patterns away from equilibrium often require compensation towards the initial position, steadily increasing the structure of the postural sway movements (Schiffman et al., 2006). Indeed, heavy loads increase injury incidence and lower physical performance (Wills et al., 2021), and by using a biomechanical approach, health-related professionals and companies which design police equipment may adequately develop policies which can help in creating and positioning ergonomically appropriate equipment on the body without large negative biomechanical effects or deviations. This study has several limitations. First, by using a cross-sectional design, we were unable to examine longitudinal changes in static foot parameters while carrying heavy loads. Second, a relatively small sample size (N = 96) may have led to insufficient statistical power. However, at the time of the study had been conducted and eligible number of participants, the sample size seemed appropriate to detect large effects between load conditions. Next, we did not collect biological and physiological parameters, which may interrogate between static foot parameters and different loading conditions. Also, no collection of data regarding injury history or how load was carried was not collected, limiting the possibility to expand our findings to practical implications towards re-positioning items and exploring potential effects of load carriage on the incidence of injuries. Finally, no 3D kinematic and muscle activation systems were assessed, limiting our findings to be observed only through a pressure platform and vertical projection of ground reaction forces. Finally, participants walked barefoot over the pressure platform, potentially limiting the generalizability and applicability of the findings to different everyday tasks of other populations of police-related field or military personnel (Lenton et al., 2019). Based on the aforementioned limitations, future longitudinal studies conducted among larger sample sizes, adjusted for potential mediators and measured with sophisticated kinematic, kinetic and electromyography systems, should be performed, in order to establish biomechanical changes and proper re-distribution load properties for minimizing injury risk. In summary, this is one of the first studies examining changes in static foot parameters under different loading conditions. The findings of the study showed that with gradually increased external loads, the center of pressure path length and velocity increased along with the major and minor axes, while changes in ground reaction forces beneath the different foot regions were not impacted by the load. Therefore, spatial and temporal parameters during quiet standing may be more prone to changes following heavy loads compared to ground reaction forces, pointing out that future research should focus on foot characteristics, rather than forces being generated beneath the feet.

9.2.Research study two

Article title

Does carrying heavy loads impact ground reaction forces and plantar pressures in intervention police officers?

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9.2.1. Abstract

Background

The main purpose of the study was to examine whether heavier loads might have an effect on ground reaction forces and plantar pressures.

Methods

Ninety-six elite intervention police officers were recruited in this cross-sectional study. Ground reaction forces and plantar pressures beneath the different foot regions were evaluated using Zebris FDM pressure platform, while a graduate increase in load carriage was as follows: (1) 'no load', (2) 'a 5-kg load', (3) 'a 25-kg load' and (4) 'a 45-kg load'.

Results

Carrying heavier loads increased ground reaction forces beneath forefoot and hindfoot regions of both feet, and midfoot region for the right foot. For plantar pressures, increases beneath the hindfoot region of both feet and midfoot region of the right foot were observed, while carrying heavier loads.

Conclusion

This study shows significant increases in both ground reaction forces and plantar pressures, especially beneath the forefoot and hindfoot regions of both feet. Since the largest forces and pressures are produced beneath the hindfoot and forefoot, future research should pay special attention to these regions and their ground absorptions, additionally preventing muscle and joint injuries.

Key words: Special populations, Gait kinetics, Heavy load, Change, Effect size

9.2.2. Introduction

Carrying excessive load represents a main component of personal mobility for successful competition of specific tasks (Birrell et al., 2007). To be able to perform at maximal level, special populations of military (Knapik et al., 2004; Joseph et al., 2018; Walsh & Low, 2021) and police (Dempsey et al., 2013; Joseph et al., 2018; Larsen et al., 2016; Lewinski et al., 2015; Ramstrand et al., 2016) personnel are required to execute highly demanding physical activities, including running, jumping and carrying heavy objects (Lockie et al., 2019; Marins et al., 2020). Although such equipment has protective effects for completing tasks and duties (Walsh & Low, 2021), evidence suggests that the load used often exceeds the recommended cut-off value of 45% body mass (Andersen et al., 2016; Orr et al., 2015). Thus, it is not surprising that extreme loading conditions may lead to changes in foot placement on the ground while absorbing various shocks during heavy load carriage (Saltzman & Nawoczenski, 1995; Scott et al., 2007). Thus, information on ground reaction forces and plantar pressures during load carriage may be relevant to describe the mechanisms of gait and to provide the magnitude of impact forces acting on the foot (Birrell et al., 2007). Moreover, both physiological and biomechanical costs of carrying heavy loads may alternatively lead to musculoskeletal and neurological injuries caused by greater forces being distributed on the foot (Orr et al., 2015; Orr et al., 2021). Indeed, a prolonged load carriage can lead to fatigue (Fallowfield et al., 2012), with longitudinal studies suggesting that knee, ankle and foot are the most common body sites of musculoskeletal pain (Orr et al., 2015; Reynolds et al., 1999). Studying the effects of carrying heavy loads on ground reaction forces (Dar et al., 2023; Goffar et al., 2013; Lenton et al., 2018; Majumdar et al., 2013; Sessoms et al., 2020; Tilbury-Davis & Hooper, 1999; Wang et al., 2023) and plantar pressures (Goffar et al., 2013; Park et al., 2013) has been mainly conducted among military personnel. Nevertheless, as one would expect, heavier loading conditions systematically lead to increases in both vertical and antero-posterior ground reaction forces produced during gait (Walsh & Low, 2021). Although the nature of an increase in ground reaction forces following heavier loads is somewhat expected, when the force is being observed on the surface as pressure, previous evidence has suggested that plantar pressures beneath different foot regions remain unchanged (Goffar et al., 2013). This would imply that force is simultaneously distributed under the specific foot regions and is not impacted by external load of different mass. Contrary to these findings, a recent study conducted among elite special police officers has shown significant changes in both ground reaction forces and plantar pressures beneath different foot regions while carrying heavy loads, pointing out that special population of police officers may be more prone to kinetic gait changes, compared to military active-duty solders (Kasović et al., 2023). In specific, a study by Kasović et al. (2023) showed gradual increases in ground reaction forces and plantar pressures under forefoot, midfoot and hindfoot regions of both feet following heavier load carriage, while temporal gait parameters, including walking speed, remained unchanged (Kasović et al., 2023). This would imply that increases in force beneath both feet might be predominantly due to the static effect of the load rather than temporal changes of the system (Birrell et al., 2007). These findings are not in line with previous protective mechanisms of changes in ground reaction forces, where heavier loads increase double support or decrease walking speed (Birrell et al., 2007; Kinoshita, 1985; Looney et al., 2021). Some evidence has also suggested that the goal of loaded walking may even minimize upper body torque, leading to a reduced likelihood of injury (LaFiandra et al., 2002). Results from the kinematic data showed that the range of motion decreased in sagittal plane knee flexion and extension and pelvis rotation in the transverse plane, while increases in adduction/abduction and rotation of the hip were observed (Birrell & Haslam, 2009). Nevertheless, it has been confirmed that changes in ground reaction forces, especially in mediolateral direction are due to a decrease in stability during a single support gait cycle, shifting the body's center of mass further away from its neutral position (Birrell et al., 2007). Similar to special police officers, intervention police officers perform vigorous physical tasks and duties on a daily basis, accompanied by even heavier load carriage exceeding >50% of body mass, compared to military personnel (Davis et al., 2016; Irving et al., 2019). The examination of the effects of carrying heavy loads on gait kinetics would potentially lead to understanding the biomechanical responses of the gait which lead to an increased injury risk. Therefore, the main purpose of the study was to investigate whether heavier loading conditions impacted ground reaction forces and plantar pressures of different foot regions in intervention police officers. We hypothesized that heavier loads would gradually lead to increases in ground reaction forces beneath different foot regions, but limited evidence would be observed for increases in plantar pressures.

9.2.3. Material and Methods

Study participants

For the purpose of this study, data were collected as described in previous studies (Kasović et al., 2023; Kasović et al., 2024). Specifically, the sample size based on G*Power calculation and using a standardized statistical power of 0.80, large effect size of 0.40 and $p < 0.05$ needed to be $N = 80$. However, we speculated that a certain drop-out rate might cause incomplete findings. By using a 20% enlargement, the final sample used for the analyses was $N = 96$. To be included in the study, participants needed to be a part of The Intervention Police Unit for a minimum of three years and without acute or chronic diseases at the time of measurement. According to the Declaration of Helsinki (World Medical Association, 2013), all procedures performed in this study were anonymous and a written informed consent was signed by all participants. This study was approved by the Ethical Committee of the Faculty of Kinesiology and the Police Intervention Department under the Ministry of Internal Affairs of the Republic of Croatia (Ethical code: 511-01-128-23-1).

Loading conditions

During testing, each participant walked over a platform and carried four types of standardized and prescribed loads proposed by the Ministry of Internal Affairs for intervention police officers: (1) body weight only ('no load'), (2) a 5-kg load ('load 1', a belt with a pistol loaded with a full handgun's magazine, an additional full handgun's magazine and handcuffs; mean weight for all participant ± SD =4.97 ± 0.25 kg), (3) a 25-kg load ('load 2', 'load 1' upgraded by a helmet, a ballistic vest and a multipurpose baton; mean weight for all participants ± SD = 20.02 ± 1.34 kg), and (4) a 45-kg load ('load 3', 'load 2' upgraded by additional protection for the lower extremities and a protective gas mask; mean weight for all participants ± SD = 45.10 ± 4.33 kg). The order of the other load was randomized, to reduce the impact of a learning effect (Kasović et al., 2023).

Ground reaction forces and plantar pressures

Ground reaction parameters recorded from the software were maximal forces beneath the forefoot, midfoot and hindfoot regions of both feet (N). Plantar parameters included peak pressures beneath the same regions of both feet (N/cm^2). Of note, the software generated the zoning of both feet. For the dynamic measurements, the load distribution beneath the forefoot, midfoot and hindfoot regions of the feet is recorded during walking over the pressure platform. Assuming normal gait without deviations or acute/chronic conditions, the load distribution under the feet during gait is shown by a semispherical load distribution under the hindfoot, followed by a contact of the entire foot with the exception of the area of the medial longitudinal arch and an even load distribution under the forefoot (the maximum load during gait is often distributed under the big toe or under the center of forefoot). Although cut-off points for high pressure have yet to be established, according to Zebris manual (Zebris Medical GmbH), the maximum load should not exceed $40\sim N/cm^2$ under the heel and $55\sim N/cm^2$ under the forefoot and all the toes should support the force exerted on the foot.

Testing procedure

To be able to calculate ground reaction forces and plantar pressures, we used a pedobarographic platform (ZEBRIS company, FDM; GmbH, Munich, Germany; number of sensors: 11,264; sampling rate: 100 Hz; sensor area: 149 cm × 54.2 cm), a simple and easy-to-administrate tool to investigate gait characteristics and followed the testing procedure in similar populations (Kasović et al., 2023; Kasović et al., 2024). Specifically, each participant walked barefoot over a platform for eight consecutive times at a self-selected walking speed with a different external load. Before and after the platform, two custom-made wooden platforms were placed, in order to establish normal gait. When the measurer gave the signal, the participant started to walk over the platform and when the end of a walkway was reached, the participant stopped, turned around and started walking towards the starting point. A cross-correlation analysis of all eight trials showed excellent reliability properties (r > 0.90). Once the measurement was completed, the load was removed, and the participants were allowed to have a resting period for at least 3 min or when heart rate was below 100 beats per minute (*Seay et al., 2014*).

Data analysis

The Kolmogorov–Smirnov test was used to assess the normality of the distribution. For normally distributed variables, basic descriptive statistics are presented as mean and standard deviation (SD). For not normally distributed variables, median and interquartile range (25th–75th) were applied. A one-way repeated measures ANOVA or the Friedman test were used to examine the differences between each loading condition. We used a Bonferroni *post-hoc* test to examine significant main effects. All statistical analyses were performed by using SPSS v23.0 software (IBM, Armonk, NY, USA) with an alpha level set a priori at p <0.05 to denote statistical significance.

9.2.4. Results

Changes in ground reaction forces and plantar pressures underneath different foot regions are presented in Table 1. Carrying heavier loads led to significant increases in maximal ground reaction forces beneath the forefoot, midfoot and hindfoot regions of the foot. In specific, the largest magnitudes of changes were observed for left and right forefoot, followed by left and right hindfoot and right midfoot, while the area under the left midfoot did not show significant changes following heavier load carriage. Bonferroni *post-hoc* analyses showed significant differences between heavier load carriage, peak plantar pressures significantly increased for the right midfoot and right and left hindfoot regions, while forefoot regions of both feet and left midfoot did not significantly change. Although not the purpose of this study, we speculated that heavier loads might also impact walking speed: that is with an increased load the walking speed would gradually decrease.

Table 1. Changes in ground reaction forces and plantar pressures under the different loading conditions.

Study variables	'No load'	'Load 1'	'Load 2'	'Load 3'	Main effect	
Ground reaction forces (max.)	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	***F*(*p*-value)**	***η*2**
Forefoot-L (N)	852.3 (109.9)[b,c,d,e]	873.0 (166.0)	960.6 (115.1)	978.4 (108.9)	23.362 (<0.001)	0.156
Forefoot-R (N)	865.6 (113.8)[b,c,d,e]	893.0 (126.7)	967.6 (115.2)	984.4 (114.2)	22.790 (<0.001)	0.153
Midfoot-L (N)	170.6 (70.3)	170.0 (74.2)	187.8 (75.4)	191.9 (82.6)	2.178 (0.090)	0.017
Midfoot-R (N)	173.9 (68.7)[c]	178.1 (75.4)	202.1 (81.4)	206.6 (82.0)	4.438 (0.004)	0.034
Hindfoot-L (N)	588.6 (89.9)[b,c,d,e]	609.5 (82.0)	651.3 (86.6)	662.2 (90.4)	15.114 (<0.001)	0.107
Hindfoot-R (N)	568.1 (84.5)[b,c,d,e]	580.5 (94.0)	617.4 (87.3)	636.6 (95.1)	11.915 (<0.001)	0.086
Plantar pressures (max.) Forefoot-L (N/cm^2)	43.8 (9.4)	43.7 (8.5)	45.7 (9.4)	46.2 (9.7)	1.843 (0.139)	0.014
Forefoot-R (N/cm^2)	44.3 (9.7)	45.2 (9.7)	47.2 (10.6)	47.7 (10.8)	2.474 (0.061)	0.019
Midfoot-L (N/cm^2)	16.6 (5.8)	16.9 (6.4)	18.4 (6.4)	18.2 (6.5)	2.220 (0.085)	0.017
Midfoot-R (N/cm^2)	15.8 (5.4)	16.3 (5.7)	18.0 (6.2)	18.2 (6.8)	4.090 (0.007)	0.031
Hindfoot-L (N/cm^2)	32.8 (6.9)	33.2 (6.6)	35.1 (7.0)	35.7 (6.7)	4.228 (0.006)	0.032
Hindfoot-R (N/cm^2)	31.6 (7.0)	32.1 (6.7)	33.7 (6.8)	34.5 (6.3)	3.983 (0.008)	0.031

Notes. [a]Significant differences between 'no load' *vs.* 'load 1'; [b]significant differences between 'no load' *vs.* 'load 2'; [c]significant differences between 'no load' *vs.* 'load 3'; [d]significant differences between 'load 1' and 'load 2'; [e]significant differences between 'load 1' and 'load 3'; [f] significant differences between 'load 2' and 'load 3'. $P < 0.05$

According to the data, walking speed remained statistically unchanged between the load conditions ('no load' = 4.44 ± 0.48 km/h; 'load 1' = 4.57 ± 0.53 km/h; 'load 2' = 4.59 ± 0.57 km/h and 'load 3' = 4.66 ± 0.68 km/h; F-value = 2.423, p = 0.066). Table 2 indicates the summary of the results in terms of an increase, decrease or no effect of load carriage on ground reaction forces and plantar pressures under the different foot regions.

Table 2. Summary of an increase, decrease or no effect of load carriage on ground reaction forces and plantar pressures for both feet.

Foot regions	**Significant main effects**
Right foot	**Forces/pressures**
Forefoot	Increased/no effect
Midfoot	Increased/increased
Hindfoot	Increased/increased
Left foot Forefoot	Increased/no effect
Midfoot	No effect/no effect
Hindfoot	Increased/increased

9.2.5. Discussion

The main purpose of the study was to investigate whether heavier loading conditions impacted ground reaction forces and plantar pressures of different foot regions in intervention police officers. The findings suggest that: (1) carrying heavier loads increases ground reaction forces beneath forefoot and hindfoot regions of both feet, and midfoot region for the right foot, and (2) with heavier loads, plantar pressures beneath the hindfoot region of both feet and midfoot region of the right foot increase. The results of this study are in line with previous findings conduced in military personnel (Dar et al., 2023; Goffar et al., 2013; Kasović et al., 2023; Lenton et al., 2018; Majumdar et al., 2013; Sessoms et al., 2020; Tilbury-Davis & Hooper, 1999; Wang et al., 2023). In a study by Goffar et al. (2013), findings showed that carrying loads of 20 kg and 40 kg significantly increased ground reaction forces beneath all foot regions. The same study performed an interaction between load and arch (normal vs. low/high) and found significant main effects beneath medial forefoot, medial midfoot and lateral hindfoot. Unfortunately, the instrumentation used in this study was pre-programmed to generate the parameters beneath the three regions of the foot along the y axis, while the information along the x axis (medial/lateral direction) was not applicable. Another study conducted among 21 army reserve males found that tibiofemoral contact forces were greater while carrying loads of 15 kg and 30 kg, compared to unloaded condition (Lenton et al., 2018). In particular, the first peak of medial compartment contact force and second peak of total contact force increased in response to increasing load magnitude. Similar findings were observed in a study by Majumdar et al. (2013), where added mass of >8.6 kg exhibited greater antero-posterior breaking forces and >6.8 kg greater antero-posterior propulsive forces, compared to unloaded condition. Moreover, a mass of >4 kg led to an increased peak vertical and propulsive impact forces, indicating that even smaller magnitudes of loads produced ground reaction force changes (Majumdar et al., 2013). Interestingly, a recent study by Sessoms et al. (2020) showed that only the first (braking) and second (propulsive) peak of antero-posterior ground reaction forces changed with heavier loads, while no significant changes in vertical or medio-lateral ground reaction forces were observed. A study conducted in special police officers confirmed the findings of this study, where heavier loading conditions (5-kg, 25-kg and 45-kg loads) increased ground reaction forces beneath the forefoot, midfoot and hindfoot regions of both feet (Kasović et al., 2023). In general, a systematic review by Walsh & Low (2021) concluded that antero-posterior breaking and/or vertical peak forces gradually increased with heavier loads, while no changes in medio-lateral ground reaction forces were observed, which is often explained by improvements in ergonomics and design in equipment over time and increases in power and work output during walking (Tilbury-Davis & Hooper, 1999). Although evidence suggests that ground reaction forces increase during added mass (Walsh & Low, 2021), previous studies aiming to investigate the effects of carrying heavy loads on plantar pressure are inconclusive. For example, some studies reported increases in absolute plantar pressures (Goffar et al., 2013; Park et al., 2013; Kasović et al., 2023) and plantar areas (Park et al., 2013), while no effects for the relative distribution of plantar pressure on the plantar surface were observed (Goffar et al., 2013). The most recent study has shown gradual increases in plantar pressures beneath the forefoot, midfoot and hindfoot regions with heavier loads (Kasović et al., 2023). The results of this study indicated that the largest and significant changes were observed beneath the hindfoot region of both feet. The hindfoot region of the foot represents the first contact with the ground which closes a kinetic chain, absorbing vertical forces and stabilizing gait during heavy loads carriage (Son, 2013). This has been supported in previous studies, showing greater increases in peak plantar pressures beneath the medial and lateral hindfoot regions, compared to other regions of the foot (Son, 2013). Increases in plantar pressures while carrying heavy loads have been reported in previous systematic reviews (Liew et al., 2016; Walsh & Low, 2021) and explained by simultaneous increases in ground reaction forces exacerbated by greater breaking and propulsive forces (Majumdar et al., 2013; Sessoms et al., 2020; Tilbury-Davis & Hooper, 1999). Increases in ground reaction forces (Dar et al., 2023; Goffar et al., 2013; Kasović et al., 2023; Lenton et al., 2018; Majumdar et al., 2013; Sessoms et al., 2020; Tilbury-Davis & Hooper, 1999; Wang et al., 2023; Walsh & Low, 2021) and plantar pressures (Goffar et al., 2013; Kasović et al., 2023; Park et al., 2013; Walsh & Low, 2021) following heavy loads carriage represent a natural response of the body to external mass, where excessive weight load increases muscular tension, particularly in lower extremities, producing larger forces and pressures in the forefoot and hindfoot regions. On the other hand, practical implications of this study may suggest that changes in ground reaction forces following heavier load carriage can lead to higher incidence of musculoskeletal injuries and disorders (Orr et al., 2021). Although we did not test the prevalence of body site injuries under different load conditions, previous studies have shown that lower back pain is the most prevalent body part being associated with prolonged heavy load (Orr & Pope, 2016), followed by knee, ankle and foot pain (Orr et al., 2015; Reynolds et al., 1999). When carrying heavy load, upper body forward lean is increased, stressing the vertebrae, intervertebral discs, muscles and spinal structures (Orr et al., 2021). Despite carrying heavy loads, acknowledging other associated factors with musculoskeletal pain, like walking/running volume (Knapik, 2014) special populations go through should be a cornerstone for implementing special policies and strategies for re-positioning load on the body and re-adjusting external mass. This is in line with previous findings, where constant load carriage over time may cause a sustained additional injury within the first 12 months of service, optimizing an injured soldier's rehabilitation process and returning to work (Orr et al., 2017). Also, by understanding mutual inter-correlations between external heavy loads, ground reaction forces and injuries and considering load mass, walking/running speed, distance covered, and type of terrain, interventions aiming to enhance the level of physical conditioning during load carriage should be advocated. This study has several limitations. First, we did not measure gait kinematics nor muscle activity properties during walking. Previous findings suggest that carrying heavy loads increases range of motions, joint impulses and moments and the activity of antigravity and propulsive trunk and leg muscles (Walsh & Low, 2021). Second, the participants were instructed to walk at self-selected speed, which can be a compensatory mechanism for altering gait locomotion to accommodate external heavy loads. By using a pre-determined treadmill walking speed, we might have observed different gait changes (Birrell & Haslam, 2009). Alternatively, studies have shown that structured questionnaires aiming to assess subjective skeletal discomfort following a load carriage exercise of 1 h may be a practical tool for injury prediction (Birrell & Haslam, 2009), which could have added more information about the musculoskeletal status of the participants in this study. Third, the load was not tested independently of how it was distributed on the body. Fourth, the testing procedure was based on walking barefoot, which is not a common practice during specific task performances. By using in-shoe insoles, we would be able to examine the effects in real situations, compared to laboratory testing. Finally, we observed somewhat asymmetrical changes between the left and the right foot, meaning that heavier loads did not impact both feet in the same magnitude. Although each participant was instructed not to target the pressure platform while walking towards it, it is possible that some participants were targeting pressure platform, unintentionally changing spatial and temporal patterns of the gait. Also, the asymmetry between the feet might have come from the first step being done with dominant vs. non-dominant foot and the compensatory mechanisms of force amortization when carrying heavier loads.

9.2.6. Conclusion

In summary, carrying heavier loads has significant effects on ground reaction forces beneath the forefoot, midfoot and hindfoot regions and on plantar pressures beneath the hindfoot region in intervention police officers. Ground reaction forces and plantar pressures gradually increase with heavier loads, pointing out that it might be appropriate to consider the tradeoffs between necessary equipment, gait kinetics and risk of injury.

9.2.7. Funding

The authors received no funding for this work.

9.2.8. Competing Interests

The authors declare there are no competing interests.

9.2.9. Author Contributions

Mario Kasović conceived and designed the experiments, authored or reviewed drafts of the article, and approved the final draft.

Davor Rožac performed the experiments, authored or reviewed drafts of the article, and approved the final draft.

Andro Štefan performed the experiments, analyzed the data, authored or reviewed drafts of the article, and approved the final draft.

Tomaš Vespalec analyzed the data, authored or reviewed drafts of the article, and approved the final draft.

Lovro Štefan conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the article, and approved the final draft.

9.2.10. Human Ethics

The following information was supplied relating to ethical approvals (*i.e.*, approving body and any reference numbers): the Ethical Committee of the Faculty of Kinesiology and the Police Intervention Department under the Ministry of Internal Affairs of the Republic of Croatia (Ethical code: 511-01-128-23-1).

9.2.11. Data Availability

The following information was supplied regarding data availability:

The raw measurements are available in the Supplementary File.

9.2.12. Supplemental Information

Supplemental information for this article can be found online at http://dx.doi.org/10.7717/peerj.16912#supplemental-information.

9.3. Research study three (paper one)

Article title

Effects of Different Load Carriage on Spatiotemporal Gait Parameters in Elite Intervention Police Officers

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9.3.1. Abstract:

Introduction

Carrying heavy loads may present certain biomechanical changes in special populations. However, most of the existing research on whether different external loads impact gait biomechanics has been conducted in military personnel, while the same changes have been relatively unknown in other populations, such as police officers. To maximize the importance of load ergonomics and design, it is necessary to establish both spatial and temporal gait changes under different load conditions in a variety of high-risk jobs, to detect which parameters are the most important for special interventions and policies. Therefore, the purpose of this study was to examine changes in spatial and temporal gait parameters under different loading conditions.

Methods

Ninety-six intervention police officers were recruited and evaluated. Zebris FDM pedobarographic platform was used to assess spatial and temporal gait changes gradual increases in load carriage significantly increased cadence ($p = 0.024$, $\eta^2 = 0.029$), stance-phase for left ($p = 0.046$, $\eta^2 = 0.024$) and right foot ($p = 0.019$, $\eta^2 = 0.030$), and load response for left ($p = 0.044$, $\eta^2 = 0.025$) and right foot ($p = 0.033$, $\eta^2 = 0.027$), while decreases in step time for left foot ($p = 0.024$, $\eta^2 = 0.029$), and swing phase for left ($p = 0.047$, $\eta^2 = 0.024$) and right foot ($p = 0.047$, $\eta^2 = 0.024$) were observed.

Results
Carrying heavier loads did not result in significant spatial gait changes ($p > 0.05$). Although non-significant, the largest magnitudes were observed for a single limb support line for both the left and right foot. For the other variables, a gradual increase in stride length, step width, and length of gait line for the left foot was observed, while a non-linear trend in other variables showed that heavier load carriage might not impact spatial gait parameters at the same rate. The spatial parameter to be almost significant was single limb support time for the right foot, where a linear decrease from 'no load' to 'load 3' was observed; however, differences remained statistically non-significant.

Conclusion
In conclusion, increases in external loads lead to larger changes in temporal, but not in spatial foot characteristics during gait. Thus, temporal gait parameters may be more prone to changes when carrying heavy loads.

Keywords: spatiotemporal parameters; gait; intervention police officers; heavy equipment; changes

9.3.2. Introduction

Carrying heavy loads represents a crucial task in a special population of military and police personnel (Knapik et al., 1996; Knapik et al., 2004; Orr, 2010). Such loads are often required for protection and providing lifesaving equipment needed for specific operations (Knapik et al., 1996; Knapik et al., 2004). Although necessary for performing fundamental tasks, evidence suggests that heavy loads often exceed a threshold of 45% of body mass recommended for long distances (Andersen et al., 2016; Orr et al., 2015). For the past years, the magnitude of the absolute load being carried has dramatically increased, showing an alarming negative trend that affects energy expenditure costs during walking (Boffey et al., 2018) and increases the risk of musculoskeletal injuries (Jennings et al., 2008). Carrying an excessive load can also impact the biomechanics of human locomotion (Boffey et al., 2018; Liew et al., 2016). During carriage, the extra load requires gait compensations to minimize decrements in maximal performance (Baggaley et al., 2020; Liew et al., 2016; Orr et al., 2014). Most parameters associated with gait include spatiotemporal data, kinematics, ground reaction forces, and electromyography (Walsh & Low, 2021). Compared to unloaded conditions, muscle activity increases with loaded conditions (Lindner et al., 2012; Paul et al., 2016; Rice et al., 2016; Sessoms et al., 2019). On the other hand, past findings have shown inconclusive results, where the added external mass can impact spatiotemporal gait parameters (Boffey et al., 2018; Liew et al., 2016), or have no proven effects (Walsh & Low, 2021). For example, previous systematic reviews have shown that external weight may lead to a reduced stride length and an increased cadence during walking (Boffey et al., 2018; Liew et al., 2016). However, the most recent systematic review has demonstrated that load carriage had no significant effect on any of the spatiotemporal gait parameters, including walking speed, step or stride length, cadence, step width, and double or single support time (Walsh & Low, 2021). Along with different findings, most of the studies have been conducted among military personnel (Walsh & Low, 2021), while the population of different types of police has been less studied. Compared to active-duty soldiers, intervention police officers are often engaged in more vigorous-intensity tasks throughout the day, possibly being at more risk for injuries and sprains (Davis et al., 2016). All these activities are accompanied by an even heavier load carriage exceeding >50% of body mass on a daily basis, compared to military personnel (Davis et al., 2016; Irving et al., 2019). This would imply that heavier load carriage and the nature of everyday tasks may have different effects on spatiotemporal gait parameters in intervention police officers. Due to these changes, previous findings on military personnel may not be applicable to this population (Walsh & Low, 2021). Therefore, the main purpose of the study was to investigate whether different loading conditions might impact spatiotemporal gait parameters in a representative sample of intervention police officers. Based on one previous study conducted on special police officers (Kasović et al., 2022), which showed non-significant changes in spatiotemporal data under different loading conditions, we hypothesized that heavier loads would lead to statistically unchanged values in both spatial and temporal gait parameters.

9.3.3. Materials and Methods

Study Participants

In this cross-sectional study, we recruited male officers of the Police Intervention Unit of the Zagreb Police Department. By using the G*Power statistical calculator to calculate the sample size and setting a statistical power of 0.80, a p-value of <0.05, and detection of large effect size (0.40), a sufficient number of subjects to participate in the study would be N = 80. Considering the potential dispersion of the sample during the implementation of the study, the sample was increased by 20% (N = 96). To be included in the study, all participants in the research were employees of the Police Intervention Unit for a minimum period of three years. Before and during the test, all participants needed to be without any acute/chronic diseases and injuries that would affect the test results or force them to drop out of the study. The research was conducted anonymously and in accordance with the Helsinki Declaration (World Medical Association Declaration of Helsinki: Ethical principles for medical research in-volving human subjects. JAMA, 2013). Before the study, a written informed consent was signed by all participants. This study was approved by the Ethical Committee of the Faculty of Kinesiology and the Police Intervention Department under the Ministry of Internal Affairs of the Republic of Croatia (Ethical code: 511-01-128-23-1).

Loading Conditions

For each loading condition, participants wore four types of loads proposed by the Ministry of Internal Affairs for intervention police officers: (1) 'no load', which only included their own body weight (2) a 5-kg load referring as 'load 1', which consisted of a belt with a loaded handgun magazine with an additional full handgun magazine and a standard set of handcuffs, (3) a 25-kg load referring as 'load 2', which represented 'load 1' + a helmet, a ballistic vest and a baton, and (4) a 45-kg load referring as 'load 3', which was a cumulative load of 'no load' + 'load 1' + 'load 2' with additional protection equipment for extremities and accompanied by a protective gas mask (Kasović et al., 2022). Previous findings have suggested that the order of the load being carried should be randomized, for the purpose of reducing a learning effect (Kasović et al., 2022). It should be noted that each load condition served for specific tasks and duties inside or outside the field for intervention police officers and these loads were chosen due to the highest amount of time being carried during working hours.

Spatiotemporal Gait Parameters

To be able to calculate spatial and temporal parameters, we used ZEBRIS FDM software (version 1.12), which generated the data after each trial. The software was connected to the pressure platform and installed on the computer, which gave us instant information regarding gait biomechanics. Pre-programmed spatial and temporal gait parameters were generated. For instance, spatial parameters recorded from the software were foot rotation in degrees, step length in cm, stride length in cm, step width in cm, length of gait line from the first to the final contact of the foot with the ground, and a single limb support line in mm. Foot rotation was calculated as the degree between the position of the foot and the line between the feet. Step length denoted the distance between the heel of one foot to the heel of the other foot and stride length summed both steps. Step width was calculated as the parallel distance between the feet. Temporal parameters included step time (in s, stride time in s, cadence as the number of steps per min, and gait speed in m/s). Step time was calculated as the time between the heels of both feet touching the ground and stride time as the summation of left and right step times. In addition, further temporal parameters recoded as % of the gait cycle for both feet were divided into two phases: (1) stance phase described by load response, mid stance, and pre-swing, and (2) swing phase. Finally, a double stance phase was generated. Of note, foot rotation, step length, length of gait line from the first to the final contact of the foot with the ground, a single support line, step time, and the % of gait cycle were calculated for both left and right foot.

Testing Procedure

We used a pressure platform (ZEBRIS company, FDM; GmbH, Munich, Germany; number of sensors: 11,264; sampling rate: 100 Hz; sensor area: 149 cm × 54.2 cm) to assess spatiotemporal gait parameters. We followed the testing procedure from previous studies (Kasović et al., 2022), which included walking at a normal pace over the platform back and forth for eight consecutive times. In brief, each participant walked over the pedobarographic platform with an additional 4.5 m custom-designed dense material platform put before and after the testing area. To be able to complete the task, the participants walked a 4.5 m platform after which they stepped and walked over the pressure platform and continued to walk across the next 4.5 m platform to the end of a walkway. When they reached the end, they rotated for 180° and continued to walk over the platform seven more times (eight trials in total). The resting period between each load was approximately 3 min or when the heart rate was below 100 beats per min (Seay et al. 2014). As highlighted in the previous section, the equipment being carried by the participants was randomized to reduce the learning effect (Kasović et al., 2022). In order to establish internal consistency between each trial, we performed the intraclass correlation coefficient for each load condition and showed excellent reliability properties of the pressure platform, ranging from 0.91 to 0.95 for both spatial and temporal gait parameters, indicating no significant deviations or variations between each trial and confirming homogeneity.

Data Analysis

The Kolmogorov–Smirnov test was used to assess the normality of the distribution. Basic descriptive statistics are presented as mean and standard deviation (SD) for normally distributed variables or as the median and interquartile range (25th–75th) for not normally distributed variables. To examine the differences between the loading conditions, a one-way repeated measures ANOVA or the Friedman test were used. Where significant main effects were observed, a modified Bonferroni *post-hoc* procedure was calculated to observe significant differences between each load condition. Partial eta squared was presented to define 'small' (0.01), 'medium' (0.06), and 'large' (0.14) effect size. Partial eta squared represents a measure of a given association which is often described as the proportion of total variation explained by an independent variable, and variance from other predictor variables from the total non-error variance. All statistical analyses were performed by using SPSS v23.0 software (IBM, Armonk, NY, USA) with an alpha level set a priori at $p < 0.05$ to denote statistical significance.

9.3.4. Results

Spatial gait changes under the different loading conditions are presented in Table 1. Carrying heavier loads did not result in significant spatial gait changes ($p > 0.05$). Although non-significant, the largest magnitudes were observed for a single limb support line for both the left and right foot. For the other variables, a gradual increase in stride length, step width, and length of gait line for the left foot was observed, while a non-linear trend in other variables showed that heavier load carriage might not impact spatial gait parameters at the same rate.

Table 1. Changes in spatial gait parameters under the different loading conditions.

Study Variables	**No Load**	**Load 1**	**Load 2**	**Load 3**	**Main Effect**	
Spinal Gait Parameters	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	**F (p-Value)**	**η^2**
Foot rotation-L (◦) *	8.3(4.9–11.4)	7.8(4.9–11.4)	8.6(5.2–11.6)	8.1(5.3–10.7)	0.509 (0.667)	0.005
Foot rotation-R (◦) *	10.1(7.4–14.7)	9.9 (6.1–14.4)	10.3(7.7–14.0)	9.9 (6.7–13.9)	0.094 (0.963)	0.001
Step length-L (cm)	68.5 (5.6)	68.7 (6.3)	68.5 (6.3)	68.9 (6.4)	0.086 (0.968)	0.001
Step length-R (cm)	67.6 (5.9)	68.7 (5.8)	68.5 (6.0)	69.0 (6.2)	0.901 (0.441)	0.008
Stride length (cm)	136.0 (10.6)	136.8 (11.0)	137.0 (11.7)	137.9 (12.0)	0.385 (0.764)	0.004
Step width (cm)	15.3 (2.9)	15.4 (2.7)	15.6 (2.8)	15.7 (2.9)	0.311 (0.817)	0.002
Length of gait line-L (mm)	239.1 (26.3)	242.4 (22.1)	245.1 (17.9)	242.7 (22.9)	1.118 (0.342)	0.009
Length of gait line-R (mm)	242.4 (18.2)	239.5 (23.6)	240.9 (24.9)	243.3 (19.4)	0.587 (0.624)	0.005
Single limb support line-L (mm)	121.6 (21.3)	127.1 (20.4)	124.8 (13.9)	123.5 (13.8)	1.382 (0.248)	0.013
Single limb support line-R (mm)	125.7 (13.0)	122.0 (15.4)	120.6 (17.2)	120.7 (14.6)	2.060 (0.105)	0.019

* denotes using median and interquartile range (25th–75th percentile); $p < 0.05$.

The spatial parameter to be almost significant was single limb support time for the right foot, where a linear decrease from 'no load' to 'load 3' was observed; however, differences remained statistically non-significant.

Table 2. Changes in temporal gait parameters under the different loading conditions.

Study Variables	**No Load**	**Load 1**	**Load 2**	**Load 3**	**Main Effect**	
Temporal Gait Parameters	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	**F (p-Value)**	**η^2**
Step time-L (s)	0.55 (0.04)	0.54 (0.04)	0.54 (0.04)	0.53 (0.04)	**3.073 (0.028)**	**0.028**
Step time-R (s)	0.55 (0.04)	0.55 (0.06)	0.55 (0.05)	0.54 (0.04)	1.702 (0.167)	0.016
Stride time (s)	1.11 (0.08)	1.09 (0.09)	1.09 (0.09)	1.07 (0.08)	2.431 (0.065)	0.022
Cadence (steps/min)	108.6 (7.7)	110.8 (7.8)	111.1 (8.4)	112.4 (8.1)	**3.191 (0.024)**	**0.029**
Gait speed (m/s)	4.44 (0.48)	4.57 (0.53)	4.59 (0.57)	4.66 (0.58)	2.423 (0.066)	0.022
Stance phase-L (%)	62.1 (2.1)	62.3 (1.9)	62.7 (1.8)	62.8 (1.9)	**2.694 (0.046)**	**0.024**
Stance phase-R (%)	62.3 (1.7)	61.6 (3.1)	62.5 (1.9)	62.5 (1.9)	**3.378 (0.019)**	**0.030**
Load response-L (%)	12.3 (1.5)	11.8 (1.6)	12.4 (1.9)	12.6 (1.5)	**2.729 (0.044)**	**0.025**
Load response-R (%)	12.0 (1.9)	12.1 (1.5)	12.7 (2.0)	12.7 (2.2)	**2.943 (0.033)**	**0.027**
Mid stance-L (%)	37.8 (1.7)	38.4 (3.0)	37.7 (2.3)	37.5 (2.1)	1.827 (0.142)	0.017
Mid stance-R (%)	37.5 (3.9)	37.5 (2.0)	37.2 (2.0)	37.2 (2.0)	0.311 (0.817)	0.003
Pre-swing-L (%)	12.1 (1.9)	12.3 (1.6)	12.5 (2.0)	12.7 (2.1)	1.686 (0.170)	0.015
Pre-swing-R (%)	12.3 (1.5)	12.2 (2.0)	12.9 (1.8)	12.7 (1.4)	**2.909 (0.035)**	**0.026**
Swing phase-L (%)	37.9 (2.1)	37.6 (1.5)	37.3 (1.8)	37.2 (1.9)	**2.688 (0.047)**	**0.024**
Swing phase-R (%)	37.7 (1.7)	38.3 (2.9)	37.5 (1.9)	375 (1.9)	**2.681 (0.047)**	**0.024**
Double stance phase (%)	24.8 (4.6)	24.3 (2.7)	25.4 (2.8)	255 (3.0)	2.132 (0.096)	0.019

$p < 0.05$

Significant decrements of values after applying heavier loads were observed for 'step- time-L', 'swing phase-L', and swing phase-R'. Specifically, significant differences were shown between the ‘no load’ and ‘load 3’ conditions for all variables. On the other hand, significant increments in values for ‘cadence’, ‘stance phase-L’, ‘stance phase-R’, ‘load response-L’, and ‘load response-R’ were observed. A *post-hoc* analysis showed that significant differences occurred between ‘no load’ and ‘load 3’ for ‘cadence’ (mean diff. −3.807, 95% CI −7.114–−0.500, p = 0.015), between ‘load 1’ and ‘load 3’ for ‘stance phase-R’ (mean diff. −0.981, 95% CI −1.897–−0.064, p = 0.029) and between ‘load 1’ and ‘load 3’ for ‘load response-R’ (mean diff. −0.751, 95% CI −1.468–−0.034, p = 0.034). No significant differences in other temporal gait parameters were detected ($p > 0.05$). Although significant temporal changes occurred, partial eta squared showed only trivial to small effect sizes between the load conditions, with the highest being obtained for the stance phase for the right foot and the lowest for the swing phase for both the left and right foot.

9.3.5. Discussion

The main purpose of the study was to investigate whether different loading conditions might impact spatiotemporal gait parameters in a representative sample of intervention police officers. The main findings of the study are: (1) no significant changes in spatial gait parameters occur when carrying heavier loads, and (2) heavier load carriage resulted in significant temporal increases for ‘cadence’, ‘stance-phase-L’, stance-phase-R’, ‘load response-L’, and ‘load response-R’ and in decreases for ‘step time-L’, ‘swing phase-L’, and ‘swing phase-R’. Findings that carrying heavy loads led to non-significant spatial gait changes are in line with previous findings (Brown et al., 2016; Coombes & Kingswell, 2005; Kasović et al., 2022; Park et al., 2013; Schulze et al., 2014). Specifically, a study by Schulze et al. (2014) conducted among 32 male active soldiers accompanied with five loading conditions performed on a treadmill showed non-significant effects of heavier loads on stride length. Similar findings have been reported in a study by Park et al. (2013), where the external load gradually increases from ‘no load’ to a ‘27-kg load’ with no marked effects on step length, step width, and gait velocity. Another two studies also showed that the additional mass had no effect on spatial gait parameters (Brown et al., 2016; Coombes & Kingswell, 2005; Kasović et al., 2022). In line with that, a recent systematic review has shown that load carriage has no proven effects on spatial gait parameters (Walsh et al., 2021). Despite mass differences between load equipment, non-significant changes in spatial gait parameters may be due to evenly distributed loads on the body, causing somewhat symmetrical gait movements without deviations or compensations (Walsh et al., 2021). However, two previous systematic reviews of Boffey et al. (2018) and Liew et al. (2016) have found altered spatial gait parameters when carrying heavy loads. It should be noted, that of three systematic reviews (Boffey et al., 2018; Liew et al., 2016; Walsh et al., 2021), two of them included a mixture of military, civilian, and unknown populations (Boffey et al., 2018; Liew et al., 2016), while the last one was conducted in military personnel (Walsh et al., 2021). The discrepancy between the findings may be related to a different response to heavy loads between military and civilian/unknown populations, where active soldiers are less affected by loads (Walsh et al., 2021). Also, different testing conditions in terms of self-paced vs. pre-determined walking speed may have resulted in different energy costs and fatigue development during task performance. This would suggest that spatial gait parameters are uninterrupted by carrying heavier loads due to their robustness to external mass (Walsh et al., 2021). We found that heavier loads carried by intervention police decreased the step time of the left foot, swing phase of both feet and increased cadence, stance phase, and load response of both feet, which is not in line with previous studies (Coombes & Kingswell, 2005; Majumdar et al., 2010; Kasović et al., 2022; Park et al., 2013; Schulze et al., 2014; Sessoms et al., 2019). Specifically, evidence suggests non-existing effects between carrying heavy loads and temporal gait parameters, such as gait speed (Kasović et al., 2022; Majumdar et al., 2010; Park et al., 2013) cadence (Coombes & Kingswell, 2005; Majumdar et al., 2010), or double and single support time (Majumdar et al., 2010), even after applying different loading strategies of backpack/backpack and armor loads (Majumdar et al., 2010; Schulze et al., 2014,; Sessoms et al., 2019), 8 kg webbing (Coombes & Kingswell, 2005), vest or body armor loads (Coombes & Kingswell, 2005; Park et al., 2013) and a rifle (Majumdar et al., 2010; Schulze et al., 2014; Sessoms et al., 2019). Although the majority of the studies found no significant effects of heavy loads on temporal parameters (Coombes & Kingswell, 2005; Kasović et al., 2022; Majumdar et al., 2010; Park et al., 2013; Schulze et al., 2014; Sessoms et al., 2019), some studies have demonstrated an increase in stance phase and double support time with external loads (Park et al., 2013), an increase in cadence and double support time when walking uphill or downhill (Fellin et al., 2016) and an increase in mid stance time (Majumdar et al., 2010). These increases in different gait phases are often explained by generating greater vertical and horizontal ground impulses to overcome the added inertial of the external load (Walsh et al., 2021). It should be highlighted that the participants in studies reporting increases in different gait phases have been instructed to walk at self-selected speeds (Majumdar et al., 2010; Park et al., 2013), as opposed to treadmill walking (Schulze et al., 2014; Sessoms et al., 2019) or running (Coombes & Kingswell, 2005). When walking speeds are self-regulated, it is possible that the time spent in different gait phases is altered and, therefore, increased to accommodate the load, while similar scenarios on a treadmill with pre-determined gait speed may alternatively mask these changes (Walsh et al., 2021). Although this study showed significant temporal, but not spatial, changes in gait parameters following heavier load carriage, the perspective of our findings is multifactorial. Based on the results, no significant spatial gait changes occurred even after carrying approximately 50% body mass, indicating that intervention police officers have developed a neuro-muscular adaptation to external heavy load after years of experience and being under constant stressful events and tasks. On the other hand, some of the temporal gait parameters significantly changed, especially in terms of cadence, pre-swing and swing gait cycles. This would imply that a single-legged part of gait under different load conditions may be more prone to changes than other temporal parameters. However, the inability to measure and track intervention police officers prior to entering the service and establish their biomechanical gait characteristics disabled us from comparing and testing the effects of standardized equipment being carried. However, from a practical point of view, we only observed very low partial eta squared, meaning that although significant temporal changes occurred, clinical implications of our data might be not relevant for taking an extra step forward for changing and re-positioning heavy equipment in intervention police officers. Unfortunately, we were unable to test the impact of previous experience of carrying heavy loads; therefore, the findings of this study should be interpreted with caution. Along with this limitation, our study has several limitations. We did not measure gait kinematics or muscle activity properties during walking. Second, a self-selected walking speed can be a compensatory mechanism for altering gait locomotion to accommodate external heavy loads. By using a pre-determined treadmill walking speed, we might have observed different gait changes. Third, the load was not tested independently of how it was distributed on the body. Fourth, the testing procedure was based on walking barefoot, which is not a common practice during specific task performances. By using in-shoe insoles, we would be able to examine the effects in real situations, compared to laboratory testing. In addition to several limitations, this study has strengths. First, we used a relatively new technology to examine spatial and temporal changes in gait biomechanics in intervention police officers, following different load conditions. For instance, the majority of previous studies have conducted their research on military personnel (Walsh et al., 2021), limiting the generalizability of the findings to other special populations. Next, a standardized load equipment was used to determine whether such external load might impact walking characteristics. Finally, compared to previous evidence (Walsh et al., 2021), a relatively large sample was recruited, which gave us the opportunity to test gait differences without the loss of statistical power. Although this study is one of the first to examine changes in spatial and temporal gait parameters in intervention police officers, based on study limitations, future research should be based on investigating these changes in different special populations (police, military, firefighters) and by including kinematics, kinetics, and electromyography properties of the gait under different load conditions, in order to establish global differences and detect these parameters that discriminated between the groups.

9.3.6. Conclusions

In summary, this study shows that carrying heavy loads does not seem to impact spatial gait parameters but leads to significant changes in some temporal gait parameters, including shorter step time and swing phase, and longer cadence, stance phase, and load response of the gait. The findings would suggest that temporal gait parameters may be more prone to changes under different loading conditions in intervention police officers, compared to spatial gait parameters. Although we observed significant temporal gait changes, trivial to small effect sizes occurred, pointing out that these changes may not be important for clinical practice or even re-distributing the load differently on the body for better ergonomics during walking. However, from a public health perspective, cumulative load carriage during a long period of time may be responsible for higher injury risk and distribution compensations in intervention police officers, showing that policymakers should pay more attention to equipment and the way of carrying it daily.

9.4. Research study three (paper two)

Article title

Spatiotemporal Gait Asymmetries Remain Unaffected by Increased Load Carriage in Professional Intervention Police Officers

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9.4.1. Abstract

Background

Although evidence indicates that load carriage may have an influence on walking patterns, the specific impacts of progressively increased loads on spatial and temporal gait asymmetries remain underexplored. Therefore, the primary aim of this study was to examine whether an increased load carriage had an effect on spatiotemporal gait asymmetries among intervention police officers.

Methods

For the purpose of this study, 96 male intervention police officers were recruited and assessed under four load conditions: (1) “No load”, (2) “a 5 kg load”, (3) “a 25 kg load”, and (4) “a 45 kg load”. Spatial and temporal gait parameters were measured using a pedobarographic platform (Zebris FDM). The spatial and temporal gait parameters, along with the ground reaction forces beneath different foot regions, were examined. The gait asymmetry for each parameter was calculated using the formula $(x_{right} - x_{left})/0.5 \times (x_{right} + x_{left})*100\%$, where “x” represents the numerical value of each parameter for the left and right sides of the body.

Results
The findings indicated no statistically significant differences in the spatiotemporal parameters, nor ground reaction force gait asymmetries between the left and right foot, while walking under a progressively increased load carriage. Additionally, the parameter values for both the left and right sides of the body remained consistent, with a high intercorrelation observed across all of the loading conditions. The gait speed and ground reaction forces, which served as covariates, did not significantly change the spatiotemporal gait asymmetries.

Conclusion
In summary, this study demonstrates that an increased load carriage did not lead to a progressive rise in spatiotemporal gait asymmetries in professional intervention police officers. However, further examination using an advanced 3D gait analysis and an assessment of physiological patterns and adaptations is recommended to identify and confirm the key factors influencing gait asymmetry.

Keywords: specialized populations; standardized load carriage; asymmetry index; differences

9.4.2. Introduction

Load carriage in specialized populations, such as police officers and their branches, has become a significant factor in ensuring protection and survival in high-risk situations (Knapik et al., 1996; Knapik et al., 2004). Indeed, carrying an external load can provide the necessary resources for daily combat tasks and missions. Although the load has its benefits, the interaction among the individual, the load, and everyday duties and responsibilities is often associated with overall health and the quality of life (Larsen et al., 2016; Salvendy, 2012). Numerous studies have investigated the effects of carrying an external load on physiological and biomechanical changes (Boffey et al., 2019; Faghy et al., 2022; Walsh et al., 2021). From a physiological perspective, it is expected that heavier loads increase total and active energy expenditure, heart rate, and breathing characteristics (Boffey et al., 2019) due to the greater forces applied on the musculoskeletal system. On the other hand, when it comes to the biomechanical approach, literature has consistently reported increased flexion in the trunk, hip, and knee, as well as greater extension moments in the knee and ankle regions of the body (Walsh et al., 2021). However, there are limited data on spatial and temporal gait characteristics, as well as the differences between the sides of the body, in response to progressively heavier external loads; these have yet to be determined. During bipedal movements, it is normal to observe a certain level of asymmetry, i.e., the inequality between the left and right sides of the body regarding a given parameter. The term “asymmetry” is one of the key factors and a starting point in defining optimal ergonomic efficiency and load positioning on the body. Thus, it is not surprising that it has gained significant attention over the last two decades (Lanshammar & Ribom, 2011; Seeley et al., 2008; Shi et al., 2015). Indeed, efforts have been made to determine an optimal level of asymmetry for certain physical performance parameters, indicating that a 15% difference between the sides of the body represents an upper threshold (Lanshammar & Ribom, 2011). However, these patterns have rarely been observed in the lower extremities, where the literature indicates an increase of up to 50% when carrying heavier loads (Seeley et al., 2008). The majority of studies have attempted to examine the effects of uneven load carriage on gait biomechanics (DeVita et al., 1991; Majumdar et al., 2013; Ozgül et al., 2012; Park et al., 2018; Shi et al., 2015; Zhang et al., 2010). When carrying an asymmetrical load, previous kinematic analyses have shown that the body naturally increases extensor moments in the hip and knee of the unloaded leg (DeVita et al., 1991). While examining joint movement during walking, little is known about the relationship between load carriage and spatiotemporal gait asymmetries (Zhang et al., 2010). The available studies on this topic have shown an increase in gait asymmetry in the ground reaction forces in the medio-lateral direction when heavier loads (up to roughly 20% of the body’s weight) are applied (Zhang et al., 2010). Most recently, a studies by Kasović et al. (2024) and Štefan et al. (2024, 2025) indicated that a 3.5 kg load significantly increased asymmetries in the gait cycle, particularly during the stance, load response, single-limb support, pre-swing, and swing phases and in the step time, compared to the no-load condition in a large sample of police recruits. However, the limitation of the aforementioned studies is its exclusive focus on a 3.5 kg load, while the effects of heavier loads on spatiotemporal gait asymmetries remain unexamined. As the authors of this study are aware, only a handful of studies have attempted to examine the effects of a gradually increasing load carriage on spatiotemporal gait asymmetries. From a practical standpoint, establishing the potential increases in gait asymmetry may result in the even greater eversion and external rotation of the foot, decreases in the step and stride length, and increases in the step and stride time (Kasović et al., 2020), which could lead to injuries and stress fractures (Sharm et al., 2014; Teyhen et al., 2020; Yavnai et al., 2021). Given the critical role of symmetrical gait in performing daily tasks and assignments, it is reasonable to propose that the addition of weight may alter the gait parameters—both temporally and spatially—and have an immediate impact on gait asymmetries. Such disparities in the values between the left and right sides of the body may lead to an altered posture, a decline in function, and an increased risk of injury. However, analyzing how body asymmetry varies under specific loading conditions may provide valuable insights for rearranging or restructuring the current loads to reduce the risk of harmful biomechanical impacts on the body during walking. Lastly, public health policymakers should gain a better understanding of load safety concerns and the potential applications of the findings. Therefore, the primary aim of this study was to examine whether an increased load carriage had effects on spatiotemporal gait asymmetries among intervention police officers. We hypothesized that gait asymmetries would gradually increase with the greater load carriage.

9.4.3. Materials and Methods

Study Participants

This observational study was conducted among male officers of the Zagreb Police Department Police Intervention Unit, who were anonymously tested. The sample size was calculated using the G*Power (version 3.1.9.7 GmbH) statistical calculator, with a statistical power of 0.80, $p < 0.05$, and a large effect size (0.40), which resulted in a sufficient sample size of N = 80 participants. Considering the dispersal of the sample during the study's implementation, an additional 20% increase was added to the sample size, resulting in N = 96. All of the subjects recruited for the study had been employees of the Police Intervention Unit for at least three years. All of the participants before and during testing were healthy and had no acute chronic illnesses or disabilities that could prevent their participation in the research or lead to the termination of their participation. Before conducting the study, written informed consent was obtained from all of the participants. The study procedure and the testing protocol were approved by the Ethical Committee of the Faculty of Kinesiology and the Police Intervention Department under the Ministry of Internal Affairs of the Republic of Croatia (Ethical code: 511-01-128-23-1).

Loading Conditions

Each test subject crossed a platform while bearing one of four standard loads recommended by the Ministry of Internal Affairs for intervention police officers. The first load was body-weight-only (referred to as "No load"); the second was a 5 kg load (referred to as "Load 1"), which consisted of a belt with a pistol that was loaded with a full handgun magazine, an additional full handgun magazine, and handcuffs; the mean weight of all of the participants was ±SD = 4.97 ± 0.25 kg. The third load was a 25 kg load (referred to as "Load 2"), which was upgraded with a helmet, a ballistic vest, and a multipurpose baton. The fourth load was a 45 kg load (referred to as "Load 3"), which was upgraded with additional lower extremity protection and a protective gas mask (or ±SD = 45.10 ± 4.33 kg). The load position in the second loading condition was around the participant's hip; for the third load, the helmet was placed on the head, while a ballistic vest was positioned on the chest region, with a multipurpose baton in front of the trunk; for the final, fourth condition, the protection was placed on the knees and arms and a protective gas mask was put behind the head. The sequence of each load was randomized to reduce the impact of a learning effect (Kasović et al., 2024).

Spatiotemporal Gait Parameters

In order to determine the spatial and temporal parameters, we used the ZEBRIS FDM 1.12. software, which produced data following each attempt. The laptop and software were connected to the platform and set up on the computer, providing immediate data on the gait biomechanics. Spatial and temporal gait parameters were created and pre-programmed within the software. For example, the software recorded spatial measurements such as foot rotation (°), step length (cm), step width (cm), the length of the gait line from first to final foot contact with the ground (mm), and a single limb support line (mm). The degree of foot rotation was determined by measuring the angle between the foot's position and the line connecting both feet. Step length refers to the distance between the heel of one foot and the heel of the other foot, while stride length combines the distances of both steps. The temporal parameters consisted of step durations (s). Step time was defined as the duration between the heel strikes of both feet upon contact with the ground. Gait speed was presented in km/h. Additionally, other temporal parameters were expressed as a percentage of the gait cycle for each foot: the stance phase, which included the load response; mid-stance; pre-swing; and the swing phase. It should be noted that foot rotation, step length, the length of the gait line from initial to final foot contact, the single support line, step time, and the percentage of the gait cycle were measured for both the left and right feet. The ground reaction forces for both feet beneath the forefoot, midfoot, and hindfoot regions were calculated and are presented in N.

Testing Procedure

In order to measure the spatiotemporal gait parameters, we utilized a pedobarographic platform from the ZEBRIS company, FDM, GmbH, Munich, Germany, which was equipped with 11,264 sensors that were operating at a sampling rate of 100 Hz and had a sensor area of 149 cm × 54.2 cm. This tool is user-friendly for studying gait characteristics, and we followed a testing procedure similar to that used in previous studies (Kasović et al., 2014). During one day of measuring all four of the levels of equipment for the members of the intervention police, we demonstrated the operation of the system and data collection to the respondents. The method of walking across the platform was explained to everyone, and it was noted that the selection of standard police equipment in different variants was chosen by random selection. Also, none of the respondents had participated in similar research, and, therefore, the effect of learning or adapting to the measurement process was avoided. Each participant carried a randomly selected load across the platform, after which, the procedure of randomly selecting equipment and walking across the platform was repeated. Two custom-built wooden platforms were positioned before and after the testing area to facilitate normal walking. Upon receiving a signal from the researcher, the participants began to move across the platform. Upon reaching the end of the walkway, the participants stopped, turned around, and headed back to their starting position. After measuring each load by randomly selecting each subject, the raw data were automatically entered into the data matrix. An analysis of cross-correlation across all eight trials demonstrated outstanding reliability ($r > 0.90$).

Statistical Analysis

To assess data normality, we employed the Kolmogorov–Smirnov test. The variables that followed normal distribution were presented as the mean and the standard deviation (SD), and the variables that were not normally distributed were presented as the median and the interquartile range (25th–75th). Asymmetries between the different loading conditions were tested using a one-way repeated measures ANOVA or the Friedman test. If a significant *p*-value was generated, a Bonferroni *post-hoc* test between the loading conditions was applied. The effect size was presented as the partial eta squared, with the following values: "small" (0.01), "medium" (0.06), and "large" (0.14). The gait asymmetries were calculated using the formula proposed by Robinson et al. (1987): $(x_{right} - x_{left})/0.5*(x_{right} + x_{left})*100\%$, where "x" represents a given parameter being calculated. A score of 0 denotes a perfectly symmetrical gait, while an increasing value in either the positive or negative direction indicates a greater asymmetry. Of note, the right side of the body was chosen habitually, and therefore, the values for the left and right sides of the body were entered into the equation. The statistical significance was set at a priori $p \leq 0.05$. All of the analyses were performed using the Statistical Package for Social Sciences (SPSS Inc., Chicago, IL, USA).

9.4.4. Results

Basic descriptive statistics and the changes between the left and right sides of the body under different loading conditions in the spatial gait parameters are presented in Table 1.

Table 1. Changes in the spatial gait parameters under the different loading conditions.

Study Variables	Left Foot	Right Foot	Mean	Symmetry Index	p	η2
Spatial Gait Parameters	**Mean (SD)**	**Mean (SD)**	**Difference**			
Foot rotation (◦) *						
No load	8.3 (4.9–11.4)	10.1 (7.4–14.7)	1.8	0.22		
Load 1	7.8 (4.9–11.4)	9.9 (6.1–14.4)	2.1	0.27		
Load 2	8.6 (5.2–11.6)	10.3 (7.7–14.0)	1.7	0.20		
Load 3	8.1 (5.3–10.7)	9.9 (6.7–13.9)	1.8	0.22	0.908	0.002
Step length (cm)						
No load	68.5 (5.6)	67.6 (5.9)	0.9	−0.02		
Load 1	68.7 (6.3)	68.7 (5.8)	0.0	0.00		
Load 2	68.5 (6.3)	68.5 (6.0)	0.0	0.00		
Load 3	68.9 (6.4)	69.0 (6.2)	0.1	0.00	0.424	0.009
Step width (cm)						
No load	15.3 (2.9)	15.3 (2.9)	/	/		
Load 1	15.4 (2.7)	15.4 (2.7)	/	/		
Load 2	15.6 (2.8)	15.6 (2.8)	/	/		
Load 3	15.7 (3.0)	15.7 (3.0)	/	/	0.759	0.003
Length of gait line (mm)						
No load	239.1 (26.3)	239.1 (26.3)	3.3	0.01		
Load 1	242.4 (22.1)	242.4 (22.1)	2.9	−0.01		
Load 2	245.1 (17.9)	245.1 (17.9)	4.2	−0.02		
Load 3	242.7 (22.9)	242.7 (22.9)	0.6	0.01	0.160	0.014
Single limb support line (mm)						
No load	121.6 (21.3)	121.6 (21.3)	4.1	0.03		
Load 1	127.1 (20.4)	127.1 (20.4)	5.1	−0.04		
Load 2	124.8 (13.9)	124.8 (13.9)	4.2	−0.03		
Load 3	123.5 (13.8)	123.5 (13.8)	2.8	−0.02	0.090	0.020

* denotes using median and interquartile range (25th–75th percentile); $p < 0.05$.

Carrying heavier loads did not result in significant changes to the spatial gait parameters, indicating that the participants maintained similar gait patterns while carrying these loads. Notably, the intercorrelation between the loading conditions for foot rotation, step length, the length of the gait line, and the single limb support line was r > 0.90, with the coefficient of variation (CV) being <1.5% within every loading condition, indicating that the participants exhibited similar spatial values and gait biomechanics. When comparing the sides of the body, the mean difference between the left and right foot was not statistically significant, which was also observed for the symmetry index.

Table 2. Changes in the temporal gait parameters under the different loading conditions.

Study Variables	**Left Foot**	**Right Foot**	**Mean**	**Symmetry Index**	**p**	**η2**
Temporal Gait Parameters	**Mean (SD)**	**Mean (SD)**	**Difference**			
Step time (s)						
No load	0.55 (0.04)	0.55 (0.04)	0.00	0.00		
Load 1	0.54 (0.04)	0.55 (0.06)	−0.01	0.02		
Load 2	0.54 (0.04)	0.55 (0.05)	−0.01	0.02		
Load 3	0.53 (0.04)	0.54 (0.04)	−0.01	0.02	0.576	0.006
Stance phase (%)						
No load	62.1 (2.1)	62.3 (1.7)	0.02	0.00		
Load 1	62.3 (1.9)	61.6 (3.1)	−0.7	−0.01		
Load 2	62.7 (1.8)	62.5 (1.9)	−0.2	0.00		
Load 3	62.8 (1.9)	62.5 (1.9)	−0.3	−0.01	0.140	0.017
Load response (%)						
No load	12.3 (1.5)	12.0 (1.9)	−0.3	−0.02		
Load 1	11.8 (1.6)	12.1 (1.5)	0.3	0.03		
Load 2	12.4 (1.9)	12.7 (2.0)	0.3	0.02		
Load 3	12.6 (1.5)	12.7 (2.2)	0.1	0.01	0.135	0.017
Mid-stance (%)						
No load	37.8 (1.7)	37.5 (3.9)	−0.3	−0.01		
Load 1	38.4 (3.0)	37.5 (2.0)	−0.9	−0.02		
Load 2	37.7 (2.3)	37.2 (2.0)	−0.5	−0.01		
Load 3	37.5 (2.1)	37.2 (2.0)	−0.3	−0.01	0.874	0.002
Pre-swing (%)						
No load	12.1 (1.9)	12.3 (1.5)	0.2	0.02		
Load 1	12.3 (1.6)	12.2 (2.0)	−0.1	−0.01		
Load 2	12.5 (2.0)	12.9 (1.8)	0.4	0.03		
Load 3	12.7 (2.1)	12.7 (1.4)	0.0	0.00	0.318	0.011
Swing phase (%)						
No load	37.9 (2.1)	37.7 (1.7)	−0.2	−0.01		
Load 1	37.6 (1.5)	38.3 (2.9)	0.7	0.02		
Load 2	37.3 (1.8)	37.5 (1.9)	0.2	0.01		
Load 3	37.2 (1.9)	37.5 (1.9)	0.2	0.01	0.161	0.016
Gait speed (km/h)						
No load	4.4 (0.5)	4.4 (0.5)	/	/		
Load 1	4.6 (0.5)	4.6 (0.5)	/	/		
Load 2	4.6 (0.6)	4.6 (0.6)	/	/		
Load 3	4.7 (0.6)	4.7 (0.6)	/	/	0.064	0.022

$p < 0.05$.

Heavier loads did not produce a greater asymmetry in the spatial gait parameters, although more substantial changes in asymmetry were observed for the single limb support line, which approached statistical significance. Foot rotation remained the most stable spatial parameter of gait across the different loading conditions. Changes in the temporal gait parameters are shown in Table 2. Similarly to the spatial gait parameters, no significant changes in any of the measured parameters were observed, irrespective of the side of the body. The intercorrelation coefficient was also extremely high ($r > 0.90$, $CV < 2.0\%$) within each side of the body. When comparing the sides of the body, the mean difference between the left and the right foot was not statistically significant, which was also observed for the symmetry index. Additionally, heavier loads did not produce a greater asymmetry in the temporal gait parameters, although more substantial changes in asymmetry were observed for the stance, load response, and swing phases of the gait. Table 3 shows changes in the ground reaction force asymmetries following the different loading conditions.

Table 3. Changes in the ground reaction force asymmetries under the different loading conditions.

Study Variables	**Left Foot**	**Right Foot**	**Mean**	**Symmetry Index**	**p**	**η2**
Temporal Gait Parameters	**Mean (SD)**	**Mean (SD)**	**Difference**			
Forefoot (N)						
No load	852.3 (109.9)	865.6 (113.8)	13.3	0.01		
Load 1	873.0 (166.0)	893.0 (126.7)	20.0	1.79		
Load 2	960.6 (115.1)	967.6 (115.2)	7.0	0.01		
Load 3	978.4 (108.9)	984.4 (114.2)	6.0	0.01	0.151	0.016
Midfoot (N)						
No load	170.6 (70.3)	173.9 (68.7)	3.3	0.08		
Load 1	170.0 (74.2)	178.1 (75.4)	8.1	0.27		
Load 2	187.8 (75.4)	202.1 (81.4)	14.3	0.13		
Load 3	191.9 (82.6)	206.6 (82.0)	14.7	0.17	0.251	0.013
Hindfoot (N)						
No load	588.6 (89.9)	568.1 (84.5)	−20.5	−0.04		
Load 1	609.5 (82.0)	580.5 (94.0)	−29.0	−0.06		
Load 2	651.3 (86.6)	617.4 (87.3)	33.9	−0.06		
Load 3	662.2 (90.4)	636.6 (95.1)	−25.6	−0.03	0.323	0.011

The findings indicated no significant changes in the force asymmetries beneath the different foot regions when a gradually heavier load was added. Of note, when each model was adjusted for gait speed and ground reaction force, similar patterns and effect sizes remained.

9.4.5. Discussion

The main purpose of this study was to examine the effects of an increased load carriage on spatiotemporal gait asymmetries in intervention police officers. The findings of the study indicate no significant differences between the left and right sides of the body, nor any expected increases in the spatial and temporal gait asymmetries following the addition of a gradually heavier load. To the authors' knowledge, thus far, no studies have explored changes in spatial and temporal gait asymmetries under different loading conditions in intervention police officers. One common approach in detecting gait imbalances typically involves measuring the ground reaction forces between the feet and the ground during a stance position (Zhang et al., 2010; Maines & Reiser, 2006). It has been shown that approximately two-thirds of the participants exhibited greater foot asymmetry in the transversal and frontal planes, compared to when carrying no load. However, limited data exists on examining the same patterns during walking. When comparing the sides of the body regarding the ground reaction forces during walking, a study by Zhang et al. (Zhang et al., 2010) found that heavier loads led to a greater asymmetry index, but the same load did not affect both feet equally. Although we hypothesized that heavier external loads would gradually produce greater spatial and temporal gait asymmetries, we did not observe such findings. One potential mechanism could be attributed to a learning effect and the participants' experience in carrying such loads on a daily basis. For example, of the three loads studied in this research, the first is often carried throughout the day, typically for 8 to 10 h. The second level of equipment is commonly used in urban situations (such as maintaining order at soccer matches, etc.), which require a higher level of risk and an additional level of protection. On average, such equipment is worn two to three times a week for approximately 12 h. The third level of equipment is intended for tasks involving the control of immigrants, terrorist attacks, etc. Intervention police officers wear this equipment for durations of 10 days to 2 weeks, for approximately 10 to 12 h per day. Given the regular use of all the levels of equipment and the extensive service experience of the intervention police officers, it is reasonable to assume that they have adapted to wearing heavier official gear, which does not significantly alter their walking patterns, particularly in the area of spatial and temporal parameters. Although we did not perform a 3D analysis of the upper extremities, it is speculated that certain adjustments were made in the inertial patterns of the musculoskeletal system due to the load placement on the body, which may have limited the natural arm swing during walking. Despite non-significant changes in asymmetry with heavier loads, the evidence implies that the trunk tends to lean away from the side carrying the load, suggesting that motor control responses to external loads may be related to load-carrying strategies and characteristics. Differences in posture between the left and right sides are influenced by the dominant side of the body, which directly affects gait asymmetry throughout the kinetic chain. Although asymmetry often occurs because of variations in stride length or cadence/walking speed (Boffey et al., 2019), the findings of this study did not reveal significant asymmetry changes in these parameters. To overcome this problem, we adjusted for gait speed and ground reaction forces, which may interact with spatial and temporal gait parameters following different loading conditions. However, we found no significant interaction effect of the aforementioned covariates in any of the models, indicating that neither gait speed nor ground reaction forces significantly affected the gait with the heavier loads. The reason for this result may be the relatively homogenous sample of intervention police officers with similar biomechanical gait patterns, constitutions, and load weights, which potentially mimic the possible effect of other habitual factors (like gait speed or ground reaction force) on gait. The second mechanism may be attributed to physiological, rather than biomechanical, responses to heavier loads, as confirmed and highlighted in other studies (Stuempfle et al., 2004; Quesada et al., 2000). From a biomechanical perspective, carrying a heavy load near the center of gravity represents the most efficient method, as it minimizes energy consumption (Heglund et al., 1995). Physiologically, previous studies have shown that an increase in load of 15% may gradually increase both resting and active energy consumption by 5–6%, due to the trunk being positioned more forward compared to the no-load condition (Quesada et al., 2000). Despite the negative findings, this study is the first to investigate both spatial and temporal gait parameters in a representative sample of intervention police officers. Although the load increments did not affect the gait patterns, the findings of this study may have practical implications for examining the movement patterns of the arms, trunk, hips, and knees, providing more detailed information regarding the various angles and angular velocity properties of the joints. Additionally, the non-significant biomechanical discrepancies in spatial and temporal gait parameters should be interpreted through the lens of physiological mechanisms and 3D kinematic and kinetic analyses, which would offer better insight into the factors contributing to these patterns. This study has several limitations. Due to its cross-sectional design, we cannot determine causal relationships regarding the asymmetries, which limits the generalizability of the findings to police recruits, who have not yet gained sufficient experience with police tasks and equipment. Second, we only examined spatiotemporal gait parameters, while 3D kinematic and electromyography systems would have provided additional insights into the increased gait asymmetries following the application of "a 3.5 kg/7.7 lb load". Third, we did not assess biological and physiological parameters, which may clarify the relationship between the dynamic foot parameters and load carriage. Additionally, we did not gather data regarding injury history or the methods of load carriage, which limits our ability to draw practical implications for repositioning load items and exploring the potential effects of load carriage on injury incidence. Fifth, previous studies have shown different systematic evaluations of the feature encoding techniques of sensory data (Fatima et al., 2024), like codebook-based and deep learning-based approaches. However, the same study confirmed that handcrafted feature-based techniques achieved a high recognition rate of approximately 96.0% for the recognition results of different human movements, showing such approaches to be as relevant as other new and more sophisticated techniques in presenting the data (Fatima et al., 2024). Finally, the participants walked barefoot over the pressure platform, which may have affected their gait patterns. Therefore, future research that is aimed at examining gait asymmetries during load carriage should focus on longitudinal study designs and comprehensive physiological and biomechanical analyses, as well as load- and injury-related characteristics. These factors may be crucial in limiting the negative effects of load carriage on the gait.

9.4.6. Practical Implications

Insignificant differences between the asymmetry of the spatial and temporal parameters of the gait using heavier equipment indicate how the members of the intervention police, as subjects of this research, achieved an established biomechanical pattern of movement in dynamic conditions. Namely, it is to be expected that asymmetries between the right and left side of the body will gradually increase, which was not the case in this study. From a practical point of view, it was determined that the different levels of equipment did not significantly affect asymmetry, which can be explained by learned motor control and ways of carrying the load itself during training or special tasks. However, there is still an unknown regarding the biomechanical differences between the right and left side of the body during long-term walking or running, which we could not confirm in this research. According to Knapik et al. (2004) and Boffey et al. (2019), the physiological component of carrying an external load can be more influenced than the biomechanical one, especially in populations that are subjected to the same or similar loads on a daily basis. Namely, it has been shown that the consumption of energy and oxygen increases physiologically during a heavy load, and the state of fatigue increases significantly (Boffey et al., 2019; Knapik et al., 2004). On the other hand, fatigue could also be measured by the time spent walking across the platform with different loads, but due to the nature of the data collection and the daily activities of the emergency police personnel, this was not possible. Nevertheless, walking at a normal and habitual pace with heavier equipment did not affect the biomechanics of the lower extremities, but other components mentioned in the Discussion Section, need to be further explored.

9.4.7. Conclusions

In summary, this study demonstrates that a heavier load carriage did not progressively increase spatial and temporal gait asymmetries in professional intervention police officers. Health and law enforcement personnel can benefit from these findings, as carrying heavy loads does not adversely affect body equilibrium or the disproportion of the gait between the left and the right sides of the body. However, other bodily functions, such as physiological changes during walking with heavier loads, should be examined and integrated into the system to identify the most significant factors influencing gait asymmetry.

9.4.8. Author Contributions

Conceptualization, M.K.; methodology, M.K.; software, D.R.; validation, D.R., M.K., and D.K.; formal analysis, D.R.; investigation, M.K.; resources, M.K.; data curation, D.R.; writing—original draft preparation, D.R., M.K., and D.K.; writing—review and editing, D.R., M.K., and D.K.; visualization, D.R.; supervision, M.K.; project administration, M.K.; funding acquisition, M.K. All authors have read and agreed to the published version of the manuscript.

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This research received no external funding.

9.4.10. Institutional Review Board Statement

This study was approved by the Ethical Committee of the Faculty of Kinesiology and the Police Intervention Department under the Ministry of Internal Affairs of the Republic of Croatia (Ethical code: 511-01-128-23-1).

9.4.11. Informed Consent Statement

All the subjects gave their informed consent for inclusion before they participated in the study.

9.4.12. Data Availability Statement

The raw data supporting the conclusions of this article will be made available by the authors on request.

9.4.13. Acknowledgments

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9.4.14. Conflicts of Interest

The authors declare no conflicts of interest.

10. GENERAL CONCLUSION

In general, carrying heavy loads is an essential part of special populations' tasks. Along with its benefits, a negative trend of an increase in heavy loads can lead to a certain delay in the feedback of the ability to maintain an upright control and posture. The findings of the study showed that with gradually increased external loads, the center of pressure path length and velocity increased along with the major and minor axes, while changes in ground reaction forces beneath the different foot regions were not impacted by the load. Therefore, the findings suggest that spatial and temporal foot parameters may be more prone to change while carrying heavy loads, especially the center of pressure characteristics. This study shows that carrying heavier loads has significant effects on ground reaction forces beneath the forefoot, midfoot and hindfoot regions and on plantar pressures beneath the hindfoot region in intervention police officers. Ground reaction forces and plantar pressures gradually increase with heavier loads, pointing out that it might be appropriate to consider the tradeoffs between necessary equipment, gait kinetics and risk of injury. However, this study shows that carrying heavy loads does not seem to impact spatial gait parameters but leads to significant changes in some temporal gait parameters, including shorter step time and swing phase, and longer cadence, stance phase, and load response of the gait. The findings would suggest that temporal gait parameters may be more prone to changes under different loading conditions in intervention police officers, compared to spatial gait parameters. Although we observed significant temporal gait changes, trivial to small effect sizes occurred, pointing out that these changes may not be important for clinical practice or even re-distributing the load differently on the body for better ergonomics during walking. However, from a public health perspective, cumulative load carriage during a long period of time may be responsible for higher injury risk and distribution compensations in intervention police officers, showing that policymakers should pay more attention to equipment and the way of carrying it on a daily basis. Also, this study demonstrates that a heavier load carriage did not progressively increase spatial and temporal gait asymmetries in professional intervention police officers. Health and law enforcement personnel can benefit from these findings, as carrying heavy loads does not adversely affect body equilibrium or the disproportion of the gait between the left and the right sides of the body. However, other bodily functions, such as physiological changes during walking with heavier loads, should be examined and integrated into the system to identify the most significant factors influencing gait asymmetry. This study has great application value, especially in today's complex security situation where police officers are often required to wear heavy and specialized equipment for long periods of time. The results can significantly improve equipment design to reduce strain, increase comfort, and minimize the risks of injuries.

10.1. Strengths and limitations

This study has several limitations. First, by using a cross-sectional design, we were unable to examine longitudinal changes in static foot parameters and in spatial and temporal gait parameters under different loading conditions. Second, a relatively small sample size (N = 96) may have led to insufficient statistical power. However, at the time of the study had been conducted and eligible number of participants, the sample size seemed appropriate to detect large effects between load conditions. Third, we did not collect biological and physiological parameters, which may interrogate between static foot parameters and different loading conditions. Next, no collection of data regarding injury history or how load was carried was not collected, limiting the possibility to expand our findings to practical implications towards re-positioning items and exploring potential effects of load carriage on the incidence of injuries. Also, no 3D kinematic and muscle activation systems were assessed, limiting our findings to be observed only through a pressure platform and vertical projection of ground reaction forces. We did not measure gait kinematics nor muscle activity properties during walking. Previous findings suggest that carrying heavy loads increases range of motions, joint impulses and moments and the activity of antigravity and propulsive trunk and leg muscles (Walsh & Low, 2021). The participants were instructed to walk at self-selected speed, which can be a compensatory mechanism for altering gait locomotion to accommodate external heavy loads. By using a pre-determined treadmill walking speed, we might have observed different gait changes (Birrell & Haslam, 2009). Alternatively, studies have shown that structured questionnaires aiming to assess subjective skeletal discomfort following a load carriage exercise of 1 h may be a practical tool for injury prediction (Birrell & Haslam, 2009), which could have added more information about the musculoskeletal status of the participants in this study. Also, the load was not tested independently of how it was distributed on the body. Next, the testing procedure was based on walking barefoot, which is not a common practice during specific task performances. By using in-shoe insoles, we would be able to examine the effects in real situations, compared to laboratory testing. Finally, we observed somewhat asymmetrical changes between the left and the right foot, meaning that heavier loads did not impact both feet in the same magnitude. Although each participant was instructed not to target the pressure platform while walking towards it, it is possible that some participants were targeting pressure platform, unintentionally changing spatial and temporal patterns of the gait. Also, the asymmetry between the feet might have come from the first step being done with dominant *vs.* non-dominant foot and the compensatory mechanisms of force amortization when carrying heavier loads.

10.2. Perspectives for future research

In summary, this is one of the first studies examining changes in the biomechanical patterns of walking and standing under different loads with the equipment of officers of the Police Intervention Unit. Based on the aforementioned limitations, future longitudinal studies conducted among larger sample sizes, adjusted for potential mediators and measured with sophisticated kinematic, kinetic and electromyography systems, should be performed, in order to establish biomechanical changes and proper re-distribution load properties for minimizing injury risk. Future research should be based on investigating these changes in different special populations (police, military, firefighters) in order to establish global differences and detect these parameters that discriminated between the groups. Future studies could investigate the effects of various footwear designs, foot orthotics, or equipment positioning during more complex running, jumping, stair climbing, or even more complex movements. This would provide a better understanding how additional police equipment affects the performance of the Intervention police officers and in executing their tasks. Future research should also explore weather cumulative load carriage during a long period of time may be responsible for higher injury risk and distribution compensations in intervention police officers, showing that policymakers should pay more attention to equipment and the way of carrying it on a daily basis.

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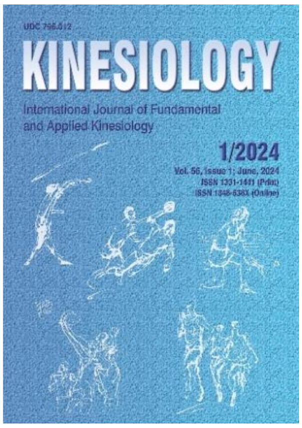
12.LIST OF APPENDICIES

12.1. Study 1

Rožac, D., Kasović, M., & Štefan, A. (2024). Impact of carrying heavy loads on postural sway and relative ground reaction forces during quiet stance in intervention police officers. *Kinesiology, 56* (1), 127-134. https://doi.org/10.26582/k.56.1.7



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IMPACT OF CARRYING HEAVY LOADS ON POSTURAL SWAY AND RELATIVE GROUND REACTION FORCES DURING QUIET STANCE IN INTERVENTION POLICE OFFICERS

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Abstract:

Although carrying heavy loads impacts gait characteristics in military personnel, less studies have examined whether a gradually load increase affects foot parameters during quiet standing in the different population of intervention police officers. Therefore, the main purpose of the study was to examine differences in postural sway and ground reaction force characteristics during a quiet stance while carrying progressively heavier equipment. Ninety-six elite intervention male police officers were assessed under four conditions: (i) 'no load', (ii) 'a 5 kg load', (iii) 'a 25 kg load', and (iv) 'a 45 kg load'. Foot characteristics during standing were assessed with the Zebris pedobarographic pressure platform. Heavier loads increased 95% confidence ellipse area ($p=.012$, $\eta2=0.028$), the center of pressure path length ($p=.010$, $\eta2=0.029$) and average velocity ($p=.011$, $\eta2=0.029$), and length of the minor ($p<.001$, $\eta2=0.040$) and major axis ($p=.004$, $\eta2=0.035$). No significant changes in relative ground reaction forces beneath the forefoot and hindfoot regions of both feet were observed ($p>.05$). The findings suggest that spatial and temporal foot parameters may be more prone to change while carrying heavy loads, especially the center of pressure characteristics.

Keywords: *special population, foot characteristics, center of pressure, statics, equipment, changes*

Introduction

Carrying excessive load represents a major part of both training and operation protocols in special population of military and police personnel (Brushøj, et al., 2008; Knapik, Reynolds & Harman, 2004; Wills, Saxby, Lenton & Doyle, 2021). Although such load is important for combat missions and specific tasks, it has been shown that it impacts optimal locomotor functions, increases the risk of lower limb injury (Wills, et al., 2021), and hampers physical performance (Boffey, et al., 2019; Martin, Kearney, Nestrowitz, Burke & Sax van der Weyden, 2023). Unfortunately, a negative trend in load weight has been observed, surpassing the recommended level of 45% of body mass (Andersen, Grimshaw, Kelso & Bentley, 2016; Orr, Coyle, Johnston & Pope, 2015). From a relative perspective, evidence shows that the load necessary for meeting tactical requirements ranges between 46% and 70% of body weight (Department of the Army, 2017).

When carrying heavy loads, an individual often tends to compensate, causing changes in gait and posture characteristics (Fox, Judge, Dickin & Wang, 2020). From a biomechanical point of view, heavy equipment during walking may impact balance, movement and overall postural stability, leading to greater torques in hip and trunk areas, which can cause alterations in body control (Heller, Challis & Sharkey, 2009). However, little evidence has been provided regarding carrying heavy loads and foot stability during quiet stance (Kasović, Vespalec & Štefan,, 2022; Richmond, Fling, Lee & Peterson 2021; Schiffman, Bensel, Hasselquist, Gregorczyk & Piscitelle , 2006; Walsh & Low, 2021;). In the process of quantifying the effects of load carriage in a stance position, first changed activity of anti-gravity muscles of the trunk should be observed, then, the postural sway as well as spatial- and temporal-related foot parameters, which may lead to higher incidence of injuries (Kroemer & Grandjean, 1997). The importance of establishing changes in biomechanical foot parameters in police officers during stance comes from a high prevalence of standing and less moving activities due to sitting in a patrol car or doing administrative tasks for a long period of time, which may lead to sedentarism (Orr, Hinton, Wilson, Pope & Dawes, 2020). The ability of standing still and remaining postural control while carrying heavy loads is important for balance control of the body, where heavier loads tend to trigger appropriate motor responses to avoid its loss or injury/fall (Pollock, Durward, Rowe & Paul, 2000). Even though a standing position seems relatively safe, an external load placement and the magnitude of an increased postural sway and a decreased base of support (considering feet together) represents one of the main problems causing muscle strains and negative body adaptations (Zultowski & Aruin, 2008). Although external load is important for survival, it may increase the risk of injury due to requirements to repetitively generate muscular force, causing whole-body fatigue and increasing energy costs connected to prolonged load carriage (Fallowfield, Blacker, Willems, Davey & Layden, 2012; Tahmasebi, Karimi, Satvati, & Fatoye, 2015). Indeed, evidence suggests that deviations of the center of pressure can predict future risk of injury and postural instability through shorter intervals in mediolateral axis (Blacker, Fallowfield, Bilzon & Willems, 2010), causing ligamentous damage, especially in the lower extremities (Knapik, et al., 2004). Both cross-sectional (Reynolds, White, Knapik, Witt & Amoroso, 1999) and longitudinal (Orr, et al., 2015; Orr, Coyle, Johnston & Pope, 2017) studies have shown that different load distribution may have even larger negative effects and can increase the level of asymmetry. Studies conducted during quiet standing have concluded that loads with a predominant mass of >40% of body weight increase pressure velocity and the contact area between the foot and the ground, directly affecting ground reaction forces beneath different foot regions (Kasović, et al., 2022; Richmond, et al., 2021; Schiffman, et al., 2006; Strube, et al., 2017; Tahmasebi, et al., 2015; Walsh & Low, 2021).

Although carrying heavy loads has been mainly observed in military personnel (Walsh & Low, 2021), studies have shown that other special populations, like police officers, may be more prone to biomechanical foot changes during quiet stance (Kasović, et al., 2022). Intervention police officers are required to perform their everyday tasks at a maximal level (Zwingmann, Zedler, Kurzner, Wahl & Goldmann, 2021). Their primary role includes intervening against crime and they are engaged in high-risk situations that often exceed the capabilities of general police (Zwingmann, et al., 2021). The most common everyday tasks are related to personal or community protection of high risk, including sports matches and events, rural operations of controlling an illegal border crossing by immigrants, or even participating in counterterrorism operations (Irving, Orr & Pope , 2019). To be able to perform at high level, intervention police officers often need to carry external loads that exceed recommended levels of 45% of body mass (Department of the Army, 2017). Since intervention police officers may carry even heavier load than military personnel and engage in more high-risk situations (Zwingmann, et al., 2021), it is necessary to examine changes in biomechanical foot parameters during quiet standing under heavy load conditions.

Therefore, the main purpose of the study was to examine whether carrying progressively heavier loads ('no load', 'a 5 kg load', 'a 25 kg load', and 'a 45 kg load') had effects on postural sway and relative ground reaction forces during quiet stance in intervention police officers. We hypothesized that officers would exhibit greater biomechanical foot changes and impaired balance under heavier loads compared to the 'no load' condition.

Methods

Study participants

In this cross-sectional study, male officers of the Police Intervention Unit of the Zagreb Police Department were recruited. Out of 280 registered intervention police officers, we were able to recruit just 96 of them due to different field-based and administrative tasks other individuals were participating in. G*Power statistical calculator was used to calculate the effect size using partial eta squared and the one-way repeated-measures ANOVA to compare the effects of load configuration, with a p-value of <.05, achieved power of 0.80, a total recruited sample size of N = 80 (out of 280 participants), four measurements, correlation among repeated measures to be set at $r = 0.50$, and a nonsphericity correction index of 1, the achieved effect size with the aforementioned number of participants was f = 0.25. Considering the potential dispersion of the sample during the study, the initial sample size of 80 participants was increased by 20%, leading to the final sample of 96 participants. All participants in the research were employees of the Zagreb Police Intervention Unit for at least three years. All participants recruited for this study were men. Sociodemographic characteristics included age (mean ± SD; 38.2 ± 10.4 years), body height (179.2 ± 12.4 cm), body mass (86.4 ± 11.3 kg), body mass index (26.9 ± 3.8 kg/m^2), and waist circumference (93.5 ± 12.6 cm). The mean age of serving as an intervention police officer was 10.3 ± 3.3 years. Out of 96 participants, seven were underweight (7.3%), 65 had normal weight (67.7%), 20 were overweight (20.8%), and four were obese (4.2%). All participants signed a written informed consent to participate and stated that they did not have any acute/chronic diseases or injuries that would affect the test results or force them to drop-out from the study. The research was conducted anonymously and in accordance with the Helsinki Declaration (World Medical Association, 2013). This study was approved by the Ethical Committee of the Faculty of Kinesiology and the Police Intervention Department under the Ministry of Internal Affairs of the Republic of Croatia (Ethical code: 511-01-128-23-1).

Loading conditions

During testing, each participant walked over a platform and carried four types of loads proposed by the Ministry of Internal Affairs for intervention police officers: (1) body weight only ('no load'), (2) a 5-kg load ('load 1', a belt with a pistol loaded with a full handgun's magazine, an additional full handgun's magazine and handcuffs), (3) a 25-kg load ('load 2'; 'load 1' upgraded by a helmet, a ballistic vest and a multipurpose baton), and (4) a 45-kg load ('load 3'; 'load 2' upgraded by the additional protection for the lower extremities and a protective gas mask). The order of the load carrying was randomized by the randomization software to reduce the impact of a learning effect (Kasović, et al., 2022). All the participants wore the same standardized equipment for each load condition. Of note, each participant wore the handgun on the dominant side of the body, which was predominantly the right side (93% of all the participants).

Static foot parameters

Measurements were conducted at the same time in the evening hours and at the same place. All respondents were familiar with the measurement protocol before the measurements. First, the anthropometric characteristics of the examinees were measured, including body height and body mass. Ground reaction forces (absolute in N and relative in %) were measured. Each participant stepped barefoot on the Zebris medical platform for the measuring of pedobarographic plantar characteristics (type FDM 1.5). The Zebris platform uses 11.264 micro sensors, arranged across the walking area, with a frequency of 300 Hz. It has been used as a diagnostic device for supporting several modes of operation, including static analysis while a participant is standing quietly (Gregory & Robertson, 2017). The Zebris platform was connected via USB cable to an external unit (laptop). The data were gathered in real time using WinFDM software for the extraction and calculation. Measurement values could be additionally exported in the form of text, picture, and video, while simultaneously comparing the data from both feet. The capacity sensor technology was based on the automatic calibration of every single sensor integrated into the platform. The task was to stand on the platform and maintain a calm position, with the arms relaxed close to the body and looking straight forward. After 15 seconds of measurement, the following parameters were generated: (i) 95% confidence ellipse area (mm^2), (ii) CoP path length (mm), (iii) CoP average velocity (mm/s), (iv) length of the minor axis, (v) length of the major axis (mm), (vi) deviation X, (vii) deviation Y, and (viii) the angle between Y and the major axis (°). For ground reaction forces, the software generated the data for the relative forces distributed under the forefoot and hindfoot regions of the foot, as well as for the total foot (%). Of note, the vertical component of the ground reaction forces was collected and analyzed as well.

Statistical analysis

Basic descriptive statistics are presented as mean and standard deviation (SD). The Kolmogorov-Smirnov test was used to assess the normality of the distribution. Pearson correlation coefficient was used to assess the level of connection between sociodemographic characteristics and changes under each load condition, to omit a potential mediation. One-way repeated-measures ANOVA was used to test the effects of load configuration ('no load', 'load 1', 'load 2' and 'load 3'). Where significant differences between load configurations were observed, a modified Bonferroni procedure was used. All statistical analyses were performed using SPSS v23.0 software (IBM, Armonk, NY, USA) with an alpha level set *a priori* at $p<.05$ to denote statistical significance.

Results

Of note, sociodemographic characteristics of the study participants were not significantly correlated to changes in stance characteristics following different load conditions ($r = 0.03 - 0.21$, $p>.05$), omitting potential mediation between a specific load condition and spatiotemporal stance changes.

Changes in static foot parameters under the different loading conditions are presented in Table 1. Significant main effects were observed for confidence ellipse area, center of pressure path length and average velocity, length of the minor and major axes and deviation X. A Bonferroni *post-hoc* analyses revealed significant differences between 'no load' and 'load 3'. Specifically, carrying 'load 3' produced significantly larger effects on the aforementioned static foot parameters compared to the 'no load' condition. Interestingly, when carrying 'load 1', the value in deviation X axis significantly decreased compared to the 'no load' condition. Insignificant main effects in other static foot

Table 1. Basic descriptive statistics and changes in static foot parameters under the different loading conditions in intervention police officers

Study variables	'No load'	'Load 1'	'Load 2'	'Load 3'	Main effect	
Static parameters	**Median (25th-75th)**	**Median (25th-75th)**	**Median (25th-75th)**	**Median (25th-75th)**	***F* (p-value)**	**η2**
Confidence ellipse area (mm²)	107.5 (68-183.5)[c]	124.5 (77.5-253.8)	144.5 (98.3-215.8)	188.5 (98.8-297.5)	**3.672 (0.012)**	**0.028**
Center of pressure path length (mm)	76.0 (63.3-91.8)[c]	81.5 (63.0-107.8)	82.0 (70.0-101.0)	91.0 (71.3-114.5)	**3.801 (0.010)**	**0.029**
Center of pressure average velocity (mm/s)	8.0 (6.0-9.0)[c]	8.0 (6.0-11.0)	8.0 (7.0-11.0)	9.0 (7.0-11.0)	**3.778 (0.011)**	**0.029**
Length of the minor axis (mm)	7.4 (5.1-9.6)[a,c]	8.3 (6.2-12.2)	8.6 (6.3-11.3)	9.1 (7.2-12.1)	**5.259 (<0.001)**	**0.040**
Length of the major axis (mm)	18.6 (14.8-24.5)[c]	22.1 (16.1-27.7)	21.1 (17.6-27.0)	23.9 (18.8-32.3)	**4.550 (0.004)**	**0.035**
Angle btween Y and the major axis (°)*	75.0 (16.0)	75.7 (14.5)	74.9 (15.4)	72.1 (20.0)	0.868 (0.458)	0.007
Deviation X (mm)	18.9 (8.4-31.0)[a]	13.9 (3.8-23.5)	17.7 (9.5-27.3)	18.4 (8.8-27.6)	**2.698 (0.046)**	**0.021**
Deviation Y (mm)	4.8 (-4.0-10.4)	6.9 (-2.2-15.2)	9.1 (-0.7-19.4)	9.3 (-2.2-17.1)	0.141 (0.935)	0.001
Relative average force-left forefoot (%)	54.1 (5.7)	55.0 (6.6)	55.5 (6.8)	55.5 (8.3)	0.884 (0.449)	0.007
Relative average force-left hindfoot (%)	45.9 (5.7)	45.1 (6.6)	44.5 (6.8)	44.5 (8.3)	0.898 (0.442)	0.007
Relative average force-left total (%)	44.9 (9.6)	46.3 (9.1)	44.1 (8.6)	44.3 (7.3)	1.233 (0.297)	0.010
Relative average force-right forefoot (%)	51.2 (7.9)	51.4 (10.1)	50.8 (8.7)	51.0 (7.7)	0.079 (0.972)	0.001
Relative average force-right hindfoot (%)	48.8 (7.9)	48.0 (8.7)	49.2 (8.7)	49.0 (7.7)	0.354 (0.787)	0.003
Relative average force-right total (%)	55.2 (9.6)	53.7 (9.1)	56.0 (8.4)	55.7 (7.3)	1.318 (0.268)	0.010

Note. [a] denotes significant differences between 'no load' and 'load 1'; [b] denotes significant differences between 'no load' and 'load 2'; [c] denotes significant differences between 'no load' and 'load 3'; [d] denotes significant differences between 'load 1' and 'load 2'; [e] denotes significant differences between 'load 1' and 'load 3'; [f] denotes significant differences between 'load 2' and 'load 3'. p<.05.

parameters were observed, pointing out that heavier equipment did not significantly impact deviation Y and relative forces under forefoot and hindfoot regions of both feet (p>.05).

Discussion and conclusions

The main purpose of the study was to examine whether heavier equipment led to changes in postural sway and relative ground reaction forces during quiet stance in intervention police officers. The main findings of the study are: (i) with the increased mass, increases in the center of pressure path length, average velocity and lengths of the minor and major axes gradually increased, and (ii) no significant changes in relative ground reaction forces beneath the forefoot and hindfoot regions of the foot were observed irrespective of heavier loads. Based on the aforementioned findings, the hypothesis of spatiotemporal and kinetic static foot changes when carrying different load could be partially confirmed, where spatiotemporal parameters led to significant changes, while relative ground reaction forces remained unchanged.

To the best of authors' knowledge, this is one of the first studies that examined whether heavier loads might impact static foot parameters in intervention police officers. Previous evidence has confirmed that heavier loads may impact several foot characteristics during quiet stance, including increases in mean postural sway during a double stance, the center of pressure path length, average velocity and lengths of the minor and major axes with a decrease in the angle between Y and the major axis (Strube et al., 2017; Walsh & Low, 2021). Specifically, a study by Strube et al. (2017) showed that mean postural sway velocity during a double leg stance increased from 0.27°·s^{-1} to 0.34°·s^{-1} when carrying 'a 16.0-kg load' and to 0.52°·s^{-1} under the '20.5-kg load', indicating a linear velocity increase while carrying heavier loads. However, the pattern of our findings clearly indicated significant differences only between 'no load' and 'load 1'/'load 3', while no other differences were observed. Unfortunately, we performed the experiment with a relatively small sample of intervention police officers; a greater sample might have led to a greater heterogeneity between the study participants in terms of their different characteristics, the duration of the load application, or the sensitivity of the postural sway measurement techniques employed. The nature of Zebris platform applied in this study was focused on vertical component (axis) of collecting the data, while antero-posterior or medio-lateral directions could not be determined. Although limited data had a significant impact on generalizability of the findings, uneven effects of carrying heavier loads on postural sway may be explained by the fact that experienced intervention police officers participated in the study, whose body adaptations were more adequate compared to new recruits. This is in line with previous evidence, where heavy load carried by young adults led to a decrease in postural stability with significant effects on the center of pressure sway area and the center of pressure anterior-posterior excursion (Martin, et al., 2023). Interestingly, studies have shown that 'a 16-kg load' may represent a significant cut-off point and result in substantial alterations in postural control (Heller, et al., 2009; Schiffman, et al., 2006; Strube, et al., 2017), compared to lighter loads, which is not in line with our findings. The *post-hoc* analysis showed that compared to the 'no load', 'a 45-kg load' led to significant changes in postural sway, mainly in the center of pressure. Of many potential factors influencing body posture, muscle activation plays an important role in maintaining an upright body posture and controls the integration of sensory systems during quiet standing (Kodithuwakku Arachchige, et al., 2020). Also, load placement relative to the body's center of mass was found to influence the amount of postural sway (Rugelj & Sevšek, 2011); when the load was placed above the center of mass, the sway parameters increased (Qu & Nussbaum, 2009). Although we were unable to test different load distribution and its impact on foot characteristics during quiet standing, studies have shown that load re-distribution towards the hips is an essential part of reducing metabolic costs and increasing contributions of hip muscles to forward progression (Jones, Canham-Chervak, Canada, Mitchener & Moore, 2010; Kavounoudias, Gilhodes, Roll & Roll, 1999). Heavier loads lead to greater foot changes and body sway during standing, which directly disrupt the body's center of mass to shift from a stable to the boundaries of the base of support, expecting a loss of balance in medio-lateral and anterior-posterior directions essential to maintain an upright stance by using the ankle and the hip compensation movements (Schiffman, et al., 2006). Losing postural stability is based on a stable system of a kinetic chain between gravity, the base of support and the center of mass. When an upright neutral position is impacted by external load, the resulting body motion is counterbalanced by one of the strategies which increases postural sway. Beside biomechanical, the physiological effects of carrying heavy loads often result in larger heart rate frequency, respiratory changes and proprioceptive systems (Horak & Nashner, 1986).

Along with postural changes, we observed no effects of carrying load on relative ground reaction forces, which is not in line with previous findings (Birrell, Hooper & Haslam, 2007; Kasović, et al., 2022; Walsh & Low, 2021). A study by Walsh and Low (2021) concluded that ground reaction forces linearly increased with heavier load. On the other hand, observing no changes in ground reaction forces was shown in a study by Goffar et al. (2013). The discrepancy in the findings may be due to different measuring modes and techniques, where the majority of the studies have been conducted in dynamic conditions, while we based the findings in static conditions. Again, more experienced officers may better compensate for heavy load, and since the load was placed near the body in this study, it is speculated that load placement away from the body may have produced different changes in ground reaction forces. Also, the software used to generate the data on calculated ground reaction forces relative to body weight, which is one of the novelties of this study. Although a quarter of the participants were overweight or obese, the interaction between body mass index and changes in postural sway or ground reaction forces were non-significant, meaning that both absolute and relative values of body mass index in our sample were homogenous and other risk factors should be taken into account when establishing the effect of load carriage on static foot parameters.

In general, carrying heavy loads is an essential part of special populations' tasks. Along with its benefits, a negative trend of an increase in heavy loads lead to a certain delay in the feedback of the ability to maintain an upright control and posture. However, body movement patterns away from equilibrium often require compensations towards the initial position, steadily increasing the structure of the postural sway movements (Schiffman, et al., 2006). Indeed, heavy loads increase injury incidence and lower physical performance (Wills, et al., 2021), and by using a biomechanical approach, health-related professionals and companies which design police equipment may adequately develop policies which can help in creating and positioning ergonomically appropriate equipment on the body without large negative biomechanical effects or deviations.

This study has several limitations. First, by using a cross-sectional design, we were unable to examine longitudinal changes in static foot parameters while carrying heavy loads. Second, a relatively small sample size (N = 96) may have led to insufficient statistical power. However, at the time of the study had been conducted and eligible number of participants, the sample size seemed appropriate to detect large effects between load conditions. Next, we did not collect biological and physiological parameters, which may interrogate between static foot parameters and different loading conditions. Also, no collection of data regarding injury history or how load was carried was not collected, limiting the possibility to expand our findings to practical implications towards re-positioning items and exploring potential effects of load carriage on the incidence of injuries. Finally, no 3D kinematic and muscle activation systems were assessed, limiting our findings to be observed only through a pressure platform and vertical projection of ground reaction forces. Finally, participants walked barefoot over the pressure platform, potentially limiting the generalizability and applicability of the findings to different everyday tasks of other populations of police-related field or military personnel (Lenton, et al., 2019). Based on the aforementioned limitations, future longitudinal studies conducted among larger sample sizes, adjusted for potential mediators and measured with sophisticated kinematic, kinetic and electromyography systems, should be performed, in order to establish biomechanical changes and proper re-distribution load properties for minimizing injury risk.

In summary, this is one of the first studies examining changes in static foot parameters under different loading conditions. The findings of the study showed that with gradually increased external loads, the center of pressure path length and velocity increased along with the major and minor axes, while changes in ground reaction forces beneath the different foot regions were not impacted by the load. Therefore, spatial and temporal parameters during quiet standing may be more prone to changes following heavy loads compared to ground reaction forces, pointing out that future research should focus on foot characteristics, rather than forces being generated beneath the feet.

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Study 2

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Does carrying heavy loads impact ground reaction forces and plantar pressures in intervention police officers?

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ABSTRACT

Background. The main purpose of the study was to examine whether heavier loads might have an effect on ground reaction forces and plantar pressures.
Methods. Ninety-six elite intervention police officers were recruited in this cross-sectional study. Ground reaction forces and plantar pressures beneath the different foot regions were evaluated using Zebris FDM pressure platform, while a graduate increase in load carriage was as following: (i) 'no load', (ii) 'a 5-kg load', (iii) 'a 25-kg load' and (iv) 'a 45-kg load'.
Results. Carrying heavier loads increased ground reaction forces beneath forefoot and hindfoot regions of both feet, and midfoot region for the right foot. For plantar pressures, increases beneath the hindfoot region of both feet and midfoot region of the right foot were observed, while carrying heavier loads.
Conclusion. This study shows significant increases in both ground reaction forces and plantar pressures, especially beneath the forefoot and hindfoot regions of both feet. Since the largest forces and pressures are produced beneath the hindfoot and forefoot, future research should pay special attention to these regions and their ground absorptions, additionally preventing from muscle and joint injuries.

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INTRODUCTION

Carrying excessive load represents a main component of personal mobility for successful competition of specific tasks (*Birrell, Hooper & Haslam, 2007*). To be able to perform at maximal level, special populations of military (*Knapik, Reynolds & Harman, 2004*; *Joseph et al., 2018*; *Walsh & Low, 2021*) and police (*Larsen, Tranberg & Ramstrand, 2016*; *Dempsey, Handcock & Rehrer, 2013*; *Lewinski et al., 2015*; *Ramstrand et al., 2016*; *Joseph et al., 2018*) personnel are required to execute highly demanding physical activities, including running, jumping and carrying heavy objects (*Lockie et al., 2019*; *Marins et al., 2020*). Although such

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equipment has protective effects for completing tasks and duties (*Walsh & Low, 2021*), evidence suggests that the load used often exceeds the recommended cut-off value of 45% body mass (*Andersen et al., 2016*; *Orr et al., 2015*). Thus, it is not surprising that extreme loading conditions may lead to changes in foot placement on the ground while absorbing various shocks during heavy load carriage (*Scott, Menz & Newcombe, 2007*; *Saltzman & Nawoczenski, 1995*). Thus, information on ground reaction forces and plantar pressures during load carriage may be relevant to describe the mechanisms of gait and to provide the magnitude of impact forces acting on the foot (*Birrell, Hooper & Haslam, 2007*). Moreover, both physiological and biomechanical costs of carrying heavy loads may alternatively lead to musculoskeletal and neurological injuries caused by greater forces being distributed on the foot (*Orr et al., 2015*; *Orr et al., 2021*). Indeed, a prolonged load carriage can lead to fatigue (*Fallowfield et al., 2012*), with longitudinal studies suggesting that knee, ankle and foot are the most common body sites of musculoskeletal pain (*Orr et al., 2015*; *Reynolds et al., 1999*).

Studying the effects of carrying heavy loads on ground reaction forces (*Goffar et al., 2013*; *Lenton et al., 2018*; *Majumdar et al., 2013*; *Sessoms et al., 2020*; *Tilbury-Davis & Hooper, 1999*; *Wang et al., 2023*; *Lenton et al., 2018*; *Dar et al., 2023*) and plantar pressures (*Goffar et al., 2013*; *Park et al., 2013*) has been mainly conducted among military personnel. Nevertheless, as one would expect, heavier loading conditions systematically lead to increases in both vertical and antero-posterior ground reaction forces produced during gait (*Walsh & Low, 2021*). Although the nature of an increase in ground reaction forces following heavier loads is somewhat expected, when the force is being observed on the surface as pressure, previous evidence has suggested that plantar pressures beneath different foot regions remain unchanged (*Goffar et al., 2013*). This would imply that force is simultaneously distributed under the specific foot regions and is not impacted by external load of different mass. Contrary to these findings, a recent study conducted among elite special police officers has shown significant changes in both ground reaction forces and plantar pressures beneath different foot regions while carrying heavy loads, pointing out that special population of police officers may be more prone to kinetic gait changes, compared to military active duty solders (*Kasović et al., 2023*). In specific, a study by *Kasović et al. (2023)* showed gradual increases in ground reaction forces and plantar pressures under forefoot, midfoot and hindfoot regions of both feet following heavier load carriage, while temporal gait parameters, including walking speed, remained unchanged (*Kasović et al., 2023*). This would imply that increases in force beneath both feet might be predominantly due to the static effect of the load rather than temporal changes of the system (*Birrell, Hooper & Haslam, 2007*). These findings are not in line with previous protective mechanisms of changes in ground reaction forces, where heavier loads increase double support or decrease walking speed (*Kinoshita, 1985*; *Birrell, Hooper & Haslam, 2007*; *Looney et al., 2021*). Some evidence has also suggested that the goal of loaded walking may even minimize upper body torque, leading to a reduced likelihood of injury (*LaFiandra et al., 2002*). Results from the kinematic data showed that the range of motion decreased in sagittal plane knee flexion and extension and pelvis rotation in the transverse plane, while increases in adduction/abduction and rotation of the hip were observed (*Birrell &*

Haslam, 2009a). Nevertheless, it has been confirmed that changes in ground reaction forces, especially in mediolateral direction are due to a decrease in stability during a single support gait cycle, shifting the body's center of mass further away from its neutral position (Birrell, Hooper & Haslam, 2007). Similar to special police officers, intervention police officers perform vigorous physical tasks and duties on a daily basis, accompanied by even heavier load carriage exceeding >50% of body mass, compared to military personnel (Davis et al., 2016; Irving, Orr & Pope, 2019). The examination of the effects of carrying heavy loads on gait kinetics would potentially lead for understanding the biomechanical responses of the gait which lead to an increased injury risk.

Therefore, the main purpose of the study was to investigate whether heavier loading conditions impacted ground reaction forces and plantar pressures of different foot regions in intervention police officers. We hypothesized, that heavier loads would gradually lead to increases in ground reaction forces beneath different foot regions, but limited evidence would be observed for increases in plantar pressures.

MATERIAL AND METHODS

Study participants

For the purpose of this study, data were collected as described in previous studies (Kasović et al., 2023; Kasović et al., 2024). Specifically, the sample size based on G*Power calculation and using a standardized statistical power of 0.80, large effect size of 0.40 and $p < 0.05$ needed to be $N = 80$. However, we speculated that a certain drop-out rate might cause incomplete findings. By using a 20% enlargement, the final sample used for the analyses was $N = 96$. To be included in the study, participants needed to be a part of Intervention Police Unit for a minimum of three years and without acute or chronic diseases at the time of measurement. According to the Declaration of Helsinki (World Medical Association, 2013), all procedures performed in this study were anonymous and a written informed consent was signed by all participants. This study was approved by the Ethical Committee of the Faculty of Kinesiology and the Police Intervention Department under the Ministry of Internal Affairs of the Republic of Croatia (Ethical code: 511-01-128-23-1).

Loading conditions

During testing, each participant walked over a platform and carried four types of standardized and prescribed loads proposed by the Ministry of Internal Affairs for intervention police officers: (1) body weight only ('no load'), (2) a 5-kg load ('load 1', a belt with a pistol loaded with a full handgun's magazine, an additional full handgun's magazine and handcuffs; mean weight for all participant ± SD =4.97 ± 0.25 kg), (3) a 25-kg load ('load 2', 'load 1' upgraded by a helmet, a ballistic vest and a multipurpose baton; mean weight for all participants ± SD = 20.02 ± 1.34 kg), and (4) a 45-kg load ('load 3', 'load 2' upgraded by additional protection for the lower extremities and a protective gas mask; mean weight for all participants ± SD = 45.10 ± 4.33 kg). The order of the other load was randomized, to reduce the impact of a learning effect (Kasović et al., 2023).

Ground reaction forces and plantar pressures

Ground reaction parameters recorded from the software were maximal forces beneath the forefoot, midfoot and hindfoot regions of both feet (N). Plantar parameters included peak pressures beneath the same regions of both feet (N/cm^2). Of note, the software generated the zoning of both feet. For the dynamic measurements, the load distribution beneath the forefoot, midfoot and hindfoot regions of the feet is recorded during walking over the pressure platform. Assuming normal gait without deviations or acute/chronic conditions, the load distribution under the feet during gait is shown by a semispherical load distribution under the hindfoot, followed by a contact of the entire foot with the exception of the area of the medial longitudinal arch and an even load distribution under the forefoot (the maximum load during gait is often distributed under the big toe or under the center of forefoot). Although cut-off points for high pressure have yet to be established, according to Zebris manual (Zebris Medical GmbH), the maximum load should not exceed 40∼N/cm^2 under the heel and 55∼N/cm^2 under the forefoot and all the toes should support the force exerted on the foot.

Testing procedure

To be able to calculate ground reaction forces and plantar pressures, we used a pedobarographic platform (ZEBRIS company, FDM; GmbH, Munich, Germany; number of sensors: 11,264; sampling rate: 100 Hz; sensor area: 149 cm × 54.2 cm), a simple and easy-to-administrate tool to investigate gait characteristics and followed the testing procedure in similar populations (*Kasović et al., 2023*; *Kasović et al., 2024*). Specifically, each participant walked barefoot over a platform for eight consecutive times at a self-selected walking speed with a different external load. Before and after the platform, two custom-made wooden platforms were placed, in order to establish normal gait. When the measurer gave the signal, the participant started to walk over the platform and when the end of a walkway was reached, the participant stopped, turned around and started walking towards the starting point. A cross-correlation analysis of all eight trials showed excellent reliability properties ($r > 0.90$). Once the measurement was completed, the load was removed and the participants were allowed to have a resting period for at least 3 min or when heart rate was below 100 beats per minute (*Seay et al., 2014*).

Data analysis

The Kolmogorov–Smirnov test was used to assess the normality of the distribution. For normally distributed variables, basic descriptive statistics are presented as mean and standard deviation (SD). For not normally distributed variables, median and interquartile range (25th–75th) were applied. A one-way repeated measures ANOVA or the Friedman test were used to examine the differences between each loading condition. We used a Bonferroni *post-hoc* test to examine significant main effects. All statistical analyses were performed by using SPSS v23.0 software (IBM, Armonk, NY, USA) with an alpha level set a priori at $p < 0.05$ to denote statistical significance.

Table 1 Changes in ground reaction forces and plantar pressures under the different loading conditions.

Study variables	'No load'	'Load 1'	'Load 2'	'Load 3'	Main effect	
Ground reaction forces (max.)	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	***F*(*p*-value)**	**$\eta 2$**
Forefoot-L (N)	852.3 (109.9)[b,c,d,e]	873.0 (166.0)	960.6 (115.1)	978.4 (108.9)	23.362 (<0.001)	0.156
Forefoot-R (N)	865.6 (113.8)[b,c,d,e]	893.0 (126.7)	967.6 (115.2)	984.4 (114.2)	22.790 (<0.001)	0.153
Midfoot-L (N)	170.6 (70.3)	170.0 (74.2)	187.8 (75.4)	191.9 (82.6)	2.178 (0.090)	0.017
Midfoot-R (N)	173.9 (68.7)[c]	178.1 (75.4)	202.1 (81.4)	206.6 (82.0)	4.438 (0.004)	0.034
Hindfoot-L (N)	588.6 (89.9)[b,c,d,e]	609.5 (82.0)	651.3 (86.6)	662.2 (90.4)	15.114 (<0.001)	0.107
Hindfoot-R (N)	568.1 (84.5)[b,c,d,e]	580.5 (94.0)	617.4 (87.3)	636.6 (95.1)	11.915 (<0.001)	0.086
Plantar pressures (max.)						
Forefoot-L (N/cm^2)	43.8 (9.4)	43.7 (8.5)	45.7 (9.4)	46.2 (9.7)	1.843 (0.139)	0.014
Forefoot-R (N/cm^2)	44.3 (9.7)	45.2 (9.7)	47.2 (10.6)	47.7 (10.8)	2.474 (0.061)	0.019
Midfoot-L (N/cm^2)	16.6 (5.8)	16.9 (6.4)	18.4 (6.4)	18.2 (6.5)	2.220 (0.085)	0.017
Midfoot-R (N/cm^2)	15.8 (5.4)	16.3 (5.7)	18.0 (6.2)	18.2 (6.8)	4.090 (0.007)	0.031
Hindfoot-L (N/cm^2)	32.8 (6.9)	33.2 (6.6)	35.1 (7.0)	35.7 (6.7)	4.228 (0.006)	0.032
Hindfoot-R (N/cm^2)	31.6 (7.0)	32.1 (6.7)	33.7 (6.8)	34.5 (6.3)	3.983 (0.008)	0.031

Notes.
[a]Significant differences between 'no load' *vs.* 'load 1'; [b]significant differences between 'no load' *vs.* 'load 2'; [c]significant differences between 'no load' *vs.* 'load 3'; [d]significant differences between 'load 1' and 'load 2'; [e]significant differences between 'load 1' and 'load 3'; [f] significant differences between 'load 2' and 'load 3'.
$P < 0.05$

RESULTS

Changes in ground reaction forces and plantar pressures underneath different foot regions are presented in Table 1. Carrying heavier loads led to significant increases in maximal ground reaction forces beneath the forefoot, midfoot and hindfoot regions of the foot. In specific, the largest magnitudes of changes were observed for left and right forefoot, followed by left and right hindfoot and right midfoot, while the area under the left midfoot did not show significant changes following heavier load carriage. Bonferroni *post-hoc* analyses showed significant differences between heavier load carriage, peak plantar pressures significantly increased for the right midfoot and right and left hindfoot regions, while forefoot regions of both feet and left midfoot did not significantly change. Although not the purpose of this study, we speculated that heavier loads might also impact walking speed: that is with an increased load the walking speed would gradually decrease. According to the data, walking speed remained statistically unchanged between the load conditions ('no load' = 4.44 ± 0.48 km/h; 'load 1' = 4.57 ± 0.53 km/h; 'load 2' = 4.59 ± 0.57 km/h and 'load 3' = 4.66 ± 0.68 km/h; F-value = 2.423, $p = 0.066$). Table 2 indicates the summary of the results in terms of an increase, decrease or no effect of load carriage on ground reaction forces and plantar pressures under the different foot regions.

DISCUSSION

The main purpose of the study was to investigate whether heavier loading conditions impacted ground reaction forces and plantar pressures of different foot regions in intervention police officers. The findings suggest that: (i) carrying heavier loads increases ground reaction forces beneath forefoot and hindfoot regions of both feet, and midfoot

Table 2 Summary of an increase, decrease or no effect of load carriage on ground reaction forces and plantar pressures for both feet.

Foot regions	Significant main effects
Right foot	**Forces/pressures**
Forefoot	Increased/no effect
Midfoot	Increased/increased
Hindfoot	Increased/increased
Left foot	
Forefoot	Increased/no effect
Midfoot	No effect/no effect
Hindfoot	Increased/increased

region for the right foot, and (ii) with heavier loads, plantar pressures beneath the hindfoot region of both feet and midfoot region of the right foot increase.

The results of this study are in line with previous findings conduced in military personnel (*Goffar et al., 2013*; *Lenton et al., 2018*; *Majumdar et al., 2013*; *Sessoms et al., 2020*; *Tilbury-Davis & Hooper, 1999*; *Wang et al., 2023*; *Kasović et al., 2023*; *Dar et al., 2023*). In a study by *Goffar et al. (2013)*, findings showed that carrying loads of 20 kg and 40 kg significantly increased ground reaction forces beneath all foot regions. The same study performed an interaction between load and arch (normal *vs.* low/high) and found significant main effects beneath medial forefoot, medial midfoot and lateral hindfoot. Unfortunately, the instrumentation used in this study was pre-programmed to generate the parameters beneath the three regions of the foot along the y axis, while the information along the x axis (medial/lateral direction) was not applicable. Another study conducted among 21 army reserve males found that tibiofemoral contact forces were greater while carrying loads of 15 kg and 30 kg, compared to unloaded condition (*Lenton et al., 2018*). In particular, the first peak of medial compartment contact force and second peak of total contact force increased in response to increasing load magnitude. Similar findings were observed in a study by *Majumdar et al. (2013)*, where added mass of >8.6 kg exhibited greater antero-posterior breaking forces and >6.8 kg greater antero-posterior propulsive forces, compared to unloaded condition. Moreover, a mass of >4 kg led to an increased peak vertical and propulsive impact forces, indicating that even smaller magnitudes of loads produced ground reaction force changes (*Majumdar et al., 2013*). Interestingly, a recent study by *Sessoms et al. (2020)* showed that only first (braking) and second (propulsive) peak of antero-posterior ground reaction forces changed with heavier loads, while no significant changes in vertical or medio-lateral ground reaction forces were observed. A study conducted in special police officers confirmed the findings of this study, where heavier loading conditions (5-kg, 25-kg and 45-kg loads) increased ground reaction forces beneath the forefoot, midfoot and hindfoot regions of both feet (*Kasović et al., 2023*). In general, a systematic review by *Walsh & Low (2021)* concluded that antero-posterior breaking and/or vertical peak forces gradually increased with heavier loads, while no changes in medio-lateral ground reaction forces were observed, which is often explained by improvements in ergonomics and design in equipment over time and increases in power and work output during walking (*Tilbury-Davis & Hooper, 1999*).

Although evidence suggests that ground reaction forces increase during added mass (*Walsh & Low, 2021*), previous studies aiming to investigate the effects of carrying heavy loads on plantar pressure are inconclusive. For example, some studies reported increases in absolute plantar pressures (*Goffar et al., 2013*; *Park et al., 2013*; *Kasović et al., 2023*) and plantar areas (*Park et al., 2013*), while no effects for the relative distribution of plantar pressure on the plantar surface were observed (*Goffar et al., 2013*). The most recent study has shown gradual increases in plantar pressures beneath the forefoot, midfoot and hindfoot regions with heavier loads (*Kasović et al., 2023*). The results of this study indicated that the largest and significant changes were observed beneath the hindfoot region of both feet. The hindfoot region of the foot represents the first contact with the ground which closes a kinetic chain, absorbing vertical forces and stabilizing gait during heavy loads carriage (*Son, 2013*). This has been supported in previous studies, showing greater increases in peak plantar pressures beneath the medial and lateral hindfoot regions, compared to other regions of the foot (*Son, 2013*). Increases in plantar pressures while carrying heavy loads have been reported in previous systematic reviews (*Liew, Morris & Netto, 2016*; *Walsh & Low, 2021*) and explained by simultaneous increases in ground reaction forces exacerbated by greater breaking and propulsive forces (*Majumdar et al., 2013*; *Sessoms et al., 2020*; *Tilbury-Davis & Hooper, 1999*).

Increases in ground reaction forces (*Goffar et al., 2013*; *Lenton et al., 2018*; *Majumdar et al., 2013*; *Sessoms et al., 2020*; *Tilbury-Davis & Hooper, 1999*; *Wang et al., 2023*; *Kasović et al., 2023*; *Dar et al., 2023*; *Walsh & Low, 2021*) and plantar pressures (*Goffar et al., 2013*; *Park et al., 2013*; *Kasović et al., 2023*; *Walsh & Low, 2021*) following heavy loads carriage represent a natural response of the body to external mass, where excessive weight load increases muscular tension, particularly in lower extremities, producing larger forces and pressures in the forefoot and hindfoot regions. On the other hand, practical implications of this study may suggest that changes in ground reaction forces following heavier load carriage can lead to higher incidence of musculoskeletal injuries and disorders (*Orr et al., 2021*). Although we did not test the prevalence of body site injuries under different load conditions, previous studies have shown that lower back pain is the most prevalent body part being associated with prolonged heavy load (*Orr & Pope, 2016*), followed by knee, ankle and foot pain (*Orr et al., 2015*; *Reynolds et al., 1999*). When carrying heavy load, upper body forward lean is increased, stressing the vertebrae, intervertebral discs, muscles and spinal structures (*Orr et al., 2021*). Despite carrying heavy loads, acknowledging other associated factors with musculoskeletal pain, like walking/running volume (*Knapik, 2014*) special populations go through should be a cornerstone for implementing special policies and strategies for re-positioning load on the body and re-adjusting external mass. This is in line with previous findings, where constant load carriage over time may cause a sustained additional injury within the first 12 months of service, optimizing an injured soldier's rehabilitation process and returning to work (*Orr et al., 2017*). Also, by understanding mutual inter-correlations between external heavy loads, ground reaction forces and injuries and taking into account load mass, walking/running speed, distance covered, and type of terrain, interventions aiming to enhance the level of physical conditioning during load carriage should be advocated.

This study has several limitations. First, we did not measure gait kinematics nor muscle activity properties during walking. Previous findings suggest that carrying heavy loads increases range of motions, joint impulses and moments and the activity of antigravity and propulsive trunk and leg muscles (*Walsh & Low, 2021*). Second, the participants were instructed to walk at self-selected speed, which can be a compensatory mechanism for altering gait locomotion to accommodate external heavy loads. By using a pre-determined treadmill walking speed, we might have observed different gait changes (*Birrell & Haslam, 2009b*). Alternatively, studies have shown that structured questionnaires aiming to assess subjective skeletal discomfort following a load carriage exercise of 1 h may be a practical tool for injury prediction (*Birrell & Haslam, 2009b*), which could have added more information about the musculoskeletal status of the participants in this study. Third, the load was not tested independently of how it was distributed on the body. Fourth, the testing procedure was based on walking barefoot, which is not a common practice during specific task performances. By using in-shoe insoles, we would be able to examine the effects in real situations, compared to laboratory testing. Finally, we observed somewhat asymmetrical changes between the left and the right foot, meaning that heavier loads did not impact both feet in the same magnitude. Although each participant was instructed not to target the pressure platform while walking towards it, it is possible that some participants were targeting pressure platform, unintentionally changing spatial and temporal patterns of the gait. Also, the asymmetry between the feet might have come from the first step being done with dominant *vs.* non-dominant foot and the compensatory mechanisms of force amortization when carrying heavier loads.

CONCLUSION

In summary, carrying heavier loads has significant effects on ground reaction forces beneath the forefoot, midfoot and hindfoot regions and on plantar pressures beneath the hindfoot region in intervention police officers. Ground reaction forces and plantar pressures gradually increase with heavier loads, pointing out that it might be appropriate to consider the tradeoffs between necessary equipment, gait kinetics and risk of injury.

ADDITIONAL INFORMATION AND DECLARATIONS

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Competing Interests

The authors declare there are no competing interests.

Author Contributions

- Mario Kasović conceived and designed the experiments, authored or reviewed drafts of the article, and approved the final draft.

- Davor Rožac performed the experiments, authored or reviewed drafts of the article, and approved the final draft.
- Andro Štefan performed the experiments, analyzed the data, authored or reviewed drafts of the article, and approved the final draft.
- Tomaš Vespalec analyzed the data, authored or reviewed drafts of the article, and approved the final draft.
- Lovro Štefan conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the article, and approved the final draft.

Human Ethics

The following information was supplied relating to ethical approvals (*i.e.*, approving body and any reference numbers):

the Ethical Committee of the Faculty of Kinesiology and the Police Intervention Department under the Ministry of Internal Affairs of the Republic of Croatia (Ethical code: 511-01-128-23-1).

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Data Availability

The following information was supplied regarding data availability:

The raw measurements are available in the Supplementary File.

Supplemental Information

Supplemental information for this article can be found online at http://dx.doi.org/10.7717/peerj.16912#supplemental-information.

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Study 3 (Paper 1)

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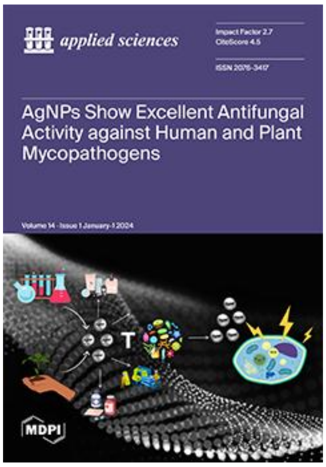

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Effects of Different Load Carriage on Spatiotemporal Gait Parameters in Elite Intervention Police Officers

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Abstract: Carrying heavy loads may present certain biomechanical changes in special populations. However, most of the existing research on whether or not different external loads impact gait biomechanics has been conducted in military personnel, while the same changes have been relatively unknown in other populations, such as police officers. In order to maximize the importance of load ergonomics and design, it is necessary to establish both spatial and temporal gait changes under different load conditions in a variety of high-risk jobs, in order to detect which parameters are the most important for special interventions and policies. Therefore, the purpose of this study was to examine changes in spatial and temporal gait parameters under different loading conditions. Ninety-six intervention police officers were recruited and evaluated. Zebris FDM pedobarographic platform was used to assess spatial and temporal gait changes gradual increases in load carriage significantly increased cadence ($p = 0.024$, $\eta^2 = 0.029$), stance-phase for left ($p = 0.046$, $\eta^2 = 0.024$) and right foot ($p = 0.019$, $\eta^2 = 0.030$), and load response for left ($p = 0.044$, $\eta^2 = 0.025$) and right foot ($p = 0.033$, $\eta^2 = 0.027$), while decreases in step time for left foot ($p = 0.024$, $\eta^2 = 0.029$), and swing phase for left ($p = 0.047$, $\eta^2 = 0.024$) and right foot ($p = 0.047$, $\eta^2 = 0.024$) were observed. No significant changes in spatial gait parameters occurred when carrying heavier loads. In conclusion, increases in external loads lead to larger changes in temporal, but not in spatial foot characteristics during gait. Thus, temporal gait parameters may be more prone to changes when carrying heavy loads.

Keywords: spatiotemporal parameters; gait; intervention police officers; heavy equipment; changes

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1. Introduction

Carrying heavy loads represents a crucial task in a special population of military and police personnel [1–3]. Such loads are often required for protection and providing lifesaving equipment needed for specific operations [1,2]. Although necessary for performing fundamental tasks, evidence suggests that heavy loads often exceed a threshold of 45% of body mass recommended for long distances [4,5]. For the past years, the magnitude of the absolute load being carried has dramatically increased, showing an alarming negative trend that affects energy expenditure costs during walking [6] and increases the risk of musculoskeletal injuries [7].

Carrying an excessive load can also impact the biomechanics of human locomotion [6,8]. During carriage, the extra load requires gait compensations to minimize decrements in maximal performance [8–10]. Most parameters associated with gait include spatiotemporal data, kinematics, ground reaction forces, and electromyography [11]. Among them, previous studies have shown that load carriage significantly impacts gait kinematics, kinetics, and electromyography [11]. In terms of kinematics, evidence suggests that during the loaded conditions, increases in hip [12,13], knee [12,14], neck [15], and trunk [12,15] flexion, ankle dorsiflexion [12] and hip [15,16], knee [15,16] and ankle [12,14,16] range of motion are observed, followed by decreases in trunk sway [17] and trunk range of motion [18]. Compared to unloaded conditions, average and peak plantar pressures [19,20] increase with loaded conditions, along with increased muscle activity [14,17,21,22]. On the other hand, past findings have shown inconclusive results, where the added external mass can impact spatiotemporal gait parameters [6,8] or have no proven effects [11]. For example, previous systematic reviews have shown that external weight may lead to a reduced stride length and an increased cadence during walking [6,8]. However, the most recent systematic review has demonstrated that load carriage had no significant effect on any of the spatiotemporal gait parameters, including walking speed, step or stride length, cadence, step width, and double or single support time [11].

Along with different findings, most of the studies have been conducted among military personnel [11], while the population of different types of police has been less studied. Compared to active-duty soldiers, intervention police officers are often engaged in more vigorous-intensity tasks throughout the day, possibly being at more risk for injuries and sprains [23]. All these activities are accompanied by even heavier load carriage exceeding >50% of body mass on a daily basis, compared to military personnel [23,24]. This would imply that heavier load carriage and the nature of everyday tasks may have different effects on spatiotemporal gait parameters in intervention police officers. Due to these changes, previous findings on military personnel may not be applicable to this population [11].

Therefore, the main purpose of the study was to investigate whether different loading conditions might impact spatiotemporal gait parameters in a representative sample of intervention police officers. Based on one previous study conducted on special police officers [25], which showed non-significant changes in spatiotemporal data under different loading conditions, we hypothesized that heavier loads would lead to statistically unchanged values in both spatial and temporal gait parameters.

2. Materials and Methods

2.1. Study Participants

In this cross-sectional study, we recruited male officers of the Police Intervention Unit of the Zagreb Police Department. By using the G*Power statistical calculator to calculate the sample size and setting a statistical power of 0.80, a p-value of <0.05, and detection of large effect size (0.40), a sufficient number of subjects to participate in the study would be N = 80. Considering the potential dispersion of the sample during the implementation of the study, the sample was increased by 20% (N = 96). To be included in the study, all participants in the research were employees of the Police Intervention Unit for a minimum period of three years. Before and during the test, all participants needed to be without any acute/chronic diseases and injuries that would affect the test results or force them to drop out of the study. The research was conducted anonymously and in accordance with the Helsinki Declaration [26]. Before the study, a written informed consent was signed by all participants. This study was approved by the Ethical Committee of the Faculty of Kinesiology and the Police Intervention Department under the Ministry of Internal Affairs of the Republic of Croatia (Ethical code: 511-01-128-23-1).

2.2. Loading Conditions

For each loading condition, participants wore four types of loads proposed by the Ministry of Internal Affairs for intervention police officers: (1) 'no load', which only included their own body weight (2) a 5-kg load referring as 'load 1', which consisted of a belt with a loaded handgun magazine with an additional full handgun magazine and a standard set of handcuffs, (3) a 25-kg load referring as 'load 2', which represented 'load 1' + a helmet, a ballistic vest and a baton, and (4) a 45-kg load referring as 'load 3', which was a cumulative load of 'no load' + 'load 1' + 'load 2' with additional protection equipment for extremities and accompanied by a protective gas mask [25]. Previous findings have suggested that the order of the load being carried should be randomized, for the purpose of reducing a learning effect [25]. It should be noted that each load condition served for specific tasks and duties inside or outside the field for intervention police officers and these loads were chosen due to the highest amount of time being carried during working hours.

2.3. Spatiotemporal Gait Parameters

To be able to calculate spatial and temporal parameters, we used ZEBRIS FDM software (version 1.12), which generated the data after each trial. The software was connected to the pressure platform and installed on the computer, which gave us instant information regarding gait biomechanics. Pre-programmed spatial and temporal gait parameters were generated. For instance, spatial parameters recorded from the software were foot rotation in degrees, step length in cm, stride length in cm, step width in cm, length of gait line from the first to the final contact of the foot with the ground, and a single limb support line in mm. Foot rotation was calculated as the degree between the position of the foot and the line between the feet. Step length denoted the distance between the heel of one foot to the heel of the other foot and stride length summed both steps. Step width was calculated as the parallel distance between the feet. Temporal parameters included step time (in s, stride time in s, cadence as the number of steps per min, and gait speed in m/s). Step time was calculated as the time between the heels of both feet touching the ground and stride time as the summation of left and right step times. In addition, further temporal parameters recoded as % of the gait cycle for both feet were divided into two phases: (i) stance phase described by load response, mid stance, and pre-swing, and (ii) swing phase. Finally, a double stance phase was generated. Of note, foot rotation, step length, length of gait line from the first to the final contact of the foot with the ground, a single support line, step time, and the % of gait cycle were calculated for both left and right foot.

2.4. Testing Procedure

We used a pressure platform (ZEBRIS company, FDM; GmbH, Munich, Germany; number of sensors: 11,264; sampling rate: 100 Hz; sensor area: 149 cm $\times$ 54.2 cm) to assess spatiotemporal gait parameters. We followed the testing procedure from previous studies [25], which included walking at a normal pace over the platform back and forth for eight consecutive times. In brief, each participant walked over the pedobarographic platform with an additional 4.5 m custom-designed dense material platform put before and after the testing area. To be able to complete the task, the participants walked a 4.5 m platform after which they stepped and walked over the pressure platform and continued to walk across the next 4.5 m platform to the end of a walkway. When they reached the end, they rotated for 180° and continued to walk over the platform seven more times (eight trials in total). The resting period between each load was approximately 3 min or when the heart rate was below 100 beats per min [16]. As highlighted in the previous section, the equipment being carried by the participants was randomized to reduce the learning effect [25]. In order to establish internal consistency between each trial, we performed the intraclass correlation coefficient for each load condition and showed excellent reliability properties of the pressure platform, ranging from 0.91 to 0.95 for both spatial and temporal gait parameters, indicating no significant deviations or variations between each trial and confirming homogeneity.

2.5. Data Analysis

The Kolmogorov–Smirnov test was used to assess the normality of the distribution. Basic descriptive statistics are presented as mean and standard deviation (SD) for normally distributed variables or as the median and interquartile range (25th–75th) for not normally distributed variables. To examine the differences between the loading conditions, a one-way repeated measures ANOVA or the Friedman test were used. Where significant main effects were observed, a modified Bonferroni *post-hoc* procedure was calculated to observe significant differences between each load condition. Partial eta squared was presented to define 'small' (0.01), 'medium' (0.06), and 'large' (0.14) effect size. Partial eta squared represents a measure of a given association which is often described as the proportion of total variation explained by an independent variable, and variance from other predictor variables from the total non-error variance. All statistical analyses were performed by using SPSS v23.0 software (IBM, Armonk, NY, USA) with an alpha level set a priori at $p < 0.05$ to denote statistical significance.

3. Results

Spatial gait changes under the different loading conditions are presented in Table 1. Carrying heavier loads did not result in significant spatial gait changes ($p > 0.05$). Although non-significant, the largest magnitudes were observed for a single limb support line for both the left and right foot. For the other variables, a gradual increase in stride length, step width, and length of gait line for the left foot was observed, while a non-linear trend in other variables showed that heavier load carriage might not impact spatial gait parameters at the same rate. The spatial parameter to be almost significant was single limb support time for the right foot, where a linear decrease from 'no load' to 'load 3' was observed; however, differences remained statistically non-significant.

Table 1. Changes in spatial gait parameters under the different loading conditions.

Study Variables	**'No Load'**	**'Load 1'**	**'Load 2'**	**'Load 3'**	**Main Effect**	
Spatial Gait Parameters	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	***F* (*p*-Value)**	η^2
Foot rotation-L (°) *	8.3 (4.9–11.4)	7.8 (4.9–11.4)	8.6 (5.2–11.6)	8.1 (5.3–10.7)	0.509 (0.667)	0.005
Foot rotation-R (°) *	10.1 (7.4–14.7)	9.9 (6.1–14.4)	10.3 (7.7–14.0)	9.9 (6.7–13.9)	0.094 (0.963)	0.001
Step length-L (cm)	68.5 (5.6)	68.7 (6.3)	68.5 (6.3)	68.9 (6.4)	0.086 (0.968)	0.001
Step length-R (cm)	67.6 (5.9)	68.7 (5.8)	68.5 (6.0)	69.0 (6.2)	0.901 (0.441)	0.008
Stride length (cm)	136.0 (10.6)	136.8 (11.0)	137.0 (11.7)	137.9 (12.0)	0.385 (0.764)	0.004
Step width (cm)	15.3 (2.9)	15.4 (2.7)	15.6 (2.8)	15.7 (2.9)	0.311 (0.817)	0.002
Length of gait line-L (mm)	239.1 (26.3)	242.4 (22.1)	245.1 (17.9)	242.7 (22.9)	1.118 (0.342)	0.009
Length of gait line-R (mm)	242.4 (18.2)	239.5 (23.6)	240.9 (24.9)	243.3 (19.4)	0.587 (0.624)	0.005
Single limb support line-L (mm)	121.6 (21.3)	127.1 (20.4)	124.8 (13.9)	123.5 (13.8)	1.382 (0.248)	0.013
Single limb support line-R (mm)	125.7 (13.0)	122.0 (15.4)	120.6 (17.2)	120.7 (14.6)	2.060 (0.105)	0.019

* denotes using median and interquartile range (25th–75th percentile); $p < 0.05$.

Table 2 shows temporal gait changes under the different loading conditions. Significant decrements of values after applying heavier loads were observed for 'step- time-L', 'swing phase-L', and swing phase-R'. Specifically, significant differences were shown between the 'no load' and 'load 3' conditions for all variables. On the other hand, significant increments in values for 'cadence', 'stance phase-L', 'stance phase-R', 'load response-L', and 'load response-R' were observed. A *post-hoc* analysis showed that significant differences occurred between 'no load' and 'load 3' for 'cadence' (mean diff. −3.807, 95% CI −7.114––0.500, $p = 0.015$), between 'load 1' and 'load 3' for 'stance phase-R' (mean diff. −0.981, 95% CI −1.897––0.064, $p = 0.029$) and between 'load 1' and 'load 3' for 'load response-R' (mean diff. −0.751, 95% CI −1.468––0.034, $p = 0.034$). No significant differences in other temporal gait parameters were detected ($p > 0.05$). Although significant temporal changes occurred, partial eta squared showed only trivial to small effect sizes between the load conditions, with the highest being obtained for the stance phase for the right foot and the lowest for the swing phase for both the left and right foot.

Table 2. Changes in temporal gait parameters under the different loading conditions.

Study Variables	'No Load'	'Load 1'	'Load 2'	'Load 3'	Main Effect	
Temporal Gait Parameters	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	***F* (*p*-Value)**	**η^2**
Step time-L (s)	0.55 (0.04)	0.54 (0.04)	0.54 (0.04)	0.53 (0.04)	**3.073 (0.028)**	**0.028**
Step time-R (s)	0.55 (0.04)	0.55 (0.06)	0.55 (0.05)	0.54 (0.04)	1.702 (0.167)	0.016
Stride time (s)	1.11 (0.08)	1.09 (0.09)	1.09 (0.09)	1.07 (0.08)	2.431 (0.065)	0.022
Cadence (steps/min)	108.6 (7.7)	110.8 (7.8)	111.1 (8.4)	112.4 (8.1)	**3.191 (0.024)**	**0.029**
Gait speed (m/s)	4.44 (0.48)	4.57 (0.53)	4.59 (0.57)	4.66 (0.58)	2.423 (0.066)	0.022
Stance phase-L (%)	62.1 (2.1)	62.3 (1.9)	62.7 (1.8)	62.8 (1.9)	**2.694 (0.046)**	**0.024**
Stance phase-R (%)	62.3 (1.7)	61.6 (3.1)	62.5 (1.9)	62.5 (1.9)	**3.378 (0.019)**	**0.030**
Load response-L (%)	12.3 (1.5)	11.8 (1.6)	12.4 (1.9)	12.6 (1.5)	**2.729 (0.044)**	**0.025**
Load response-R (%)	12.0 (1.9)	12.1 (1.5)	12.7 (2.0)	12.7 (2.2)	**2.943 (0.033)**	**0.027**
Mid stance-L (%)	37.8 (1.7)	38.4 (3.0)	37.7 (2.3)	37.5 (2.1)	1.827 (0.142)	0.017
Mid stance-R (%)	37.5 (3.9)	37.5 (2.0)	37.2 (2.0)	37.2 (2.0)	0.311 (0.817)	0.003
Pre-swing-L (%)	12.1 (1.9)	12.3 (1.6)	12.5 (2.0)	12.7 (2.1)	1.686 (0.170)	0.015
Pre-swing-R (%)	12.3 (1.5)	12.2 (2.0)	12.9 (1.8)	12.7 (1.4)	**2.909 (0.035)**	**0.026**
Swing phase-L (%)	37.9 (2.1)	37.6 (1.5)	37.3 (1.8)	37.2 (1.9)	**2.688 (0.047)**	**0.024**
Swing phase-R (%)	37.7 (1.7)	38.3 (2.9)	37.5 (1.9)	375 (1.9)	**2.681 (0.047)**	**0.024**
Double stance phase (%)	24.8 (4.6)	24.3 (2.7)	25.4 (2.8)	255 (3.0)	2.132 (0.096)	0.019

$p < 0.05$.

4. Discussion

The main purpose of the study was to investigate whether different loading conditions might impact spatiotemporal gait parameters in a representative sample of intervention police officers. The main findings of the study are: (i) no significant changes in spatial gait parameters occur when carrying heavier loads, and (ii) heavier load carriage resulted in significant temporal increases for 'cadence', 'stance-phase-L', stance-phase-R', 'load response-L', and 'load response-R' and in decreases for 'step time-L', 'swing phase-L', and 'swing phase-R'.

Findings that carrying heavy loads led to non-significant spatial gait changes are in line with previous findings [13,20,25,27,28]. Specifically, a study by Schulze et al. [13] conducted among 32 male active soldiers accompanied with five loading conditions performed on a treadmill showed non-significant effects of heavier loads on stride length. Similar findings have been reported in a study by Park et al. [20], where the external load gradually increases from 'no load' to a '27-kg load' with no marked effects on step length, step width, and gait velocity. Another two studies also showed that the additional mass had no effect on spatial gait parameters [25,27,28]. In line with that, a recent systematic review has shown that load carriage has no proven effects on spatial gait parameters [11]. Despite mass differences between load equipment, non-significant changes in spatial gait parameters may be due to evenly distributed loads on the body, causing somewhat symmetrical gait movements without deviations or compensations [11]. However, two previous systematic reviews of Boffey et al. [6] and Liew et al. [8] have found altered spatial gait parameters when carrying heavy loads. It should be noted, that of three systematic reviews [6,8,11], two of them included a mixture of military, civilian, and unknown populations [6,8], while the last one was conducted in military personnel [11]. The discrepancy between the findings may be related to a different response to heavy loads between military and civilian/unknown populations, where active soldiers are less affected by loads [11]. Also, different testing conditions in terms of self-paced vs. pre-determined walking speed may have resulted in different energy costs and fatigue development during task performance. This would suggest that spatial gait parameters are uninterrupted by carrying heavier loads due to their robustness to external mass [11].

We found that heavier loads carried by intervention police decreased the step time of the left foot, swing phase of both feet and increased cadence, stance phase, and load response of both feet, which is not in line with previous studies [12,13,17,20,25,28]. Specifically, evidence suggests non-existing effects between carrying heavy loads and temporal gait parameters, such as gait speed [12,20,25], cadence [12,28], or double and single support time [12], even after applying different loading strategies of backpack/backpack and armor loads [12,13,17], 8 kg webbing [28], vest or body armor loads [20,28] and a rifle [12,13,17]. Although the majority of the studies found no significant effects of heavy loads on temporal parameters [12,13,17,20,25,28], some studies have demonstrated an increase in stance phase and double support time with external loads [20], an increase in cadence and double support time when walking uphill or downhill [29] and an increase in mid stance time [12]. These increases in different gait phases are often explained by generating greater vertical and horizontal ground impulses to overcome the added inertial of the external load [11]. It should be highlighted that the participants in studies reporting increases in different gait phases have been instructed to walk at self-selected speeds [12,20], as opposed to treadmill walking [13,17] or running [28]. When walking speeds are self-regulated, it is possible that the time spent in different gait phases is altered and, therefore, increased to accommodate the load, while similar scenarios on a treadmill with pre-determined gait speed may alternatively mask these changes [11].

Although this study showed significant temporal, but not spatial, changes in gait parameters following heavier load carriage, the perspective of our findings is multifactorial. Based on the results, no significant spatial gait changes occurred even after carrying approximately 50% body mass, indicating that intervention police officers have developed a neuro-muscular adaptation to external heavy load after years of experience and being under constant stressful events and tasks. On the other hand, some of the temporal gait parameters significantly changed, especially in terms of cadence, pre-swing and swing gait cycles. This would imply that a single-legged part of gait under different load conditions may be more prone to changes than other temporal parameters. However, the inability to measure and track intervention police officers prior to entering the service and establish their biomechanical gait characteristics disabled us from comparing and testing the effects of standardized equipment being carried. However, from a practical point of view, we only observed very low partial eta squared, meaning that although significant temporal changes occurred, clinical implications of our data might be not relevant for taking an extra step forward for changing and re-positioning heavy equipment in intervention police officers. Unfortunately, we were unable to test the impact of previous experience of carrying heavy loads; therefore, the findings of this study should be interpreted with caution. Along with this limitation, our study has several limitations. We did not measure gait kinematics or muscle activity properties during walking. Second, a self-selected walking speed can be a compensatory mechanism for altering gait locomotion to accommodate external heavy loads. By using a pre-determined treadmill walking speed, we might have observed different gait changes. Third, the load was not tested independently of how it was distributed on the body. Fourth, the testing procedure was based on walking barefoot, which is not a common practice during specific task performances. By using in-shoe insoles, we would be able to examine the effects in real situations, compared to laboratory testing. In addition to several limitations, this study has strengths. First, we used a relatively new technology to examine spatial and temporal changes in gait biomechanics in intervention police officers, following different load conditions. For instance, the majority of previous studies have conducted their research on military personnel [11], limiting the generalizability of the findings to other special populations. Next, a standardized load equipment was used to determine whether such external load might impact walking characteristics. Finally, compared to previous evidence [11], a relatively large sample was recruited, which gave us the opportunity to test gait differences without the loss of statistical power. Although this study is one of the first to examine changes in spatial and temporal gait parameters in intervention police officers, based on study limitations, future research should be based on investigating these changes in different special populations (police, military, firefighters) and by including kinematics, kinetics, and electromyography properties of the gait under different load conditions, in order to establish global differences and detect these parameters that discriminated between the groups.

5. Conclusions

In summary, this study shows that carrying heavy loads does not seem to impact spatial gait parameters, but leads to significant changes in some temporal gait parameters, including shorter step time and swing phase, and longer cadence, stance phase, and load response of the gait. The findings would suggest that temporal gait parameters may be more prone to changes under different loading conditions in intervention police officers, compared to spatial gait parameters. Although we observed significant temporal gait changes, trivial to small effect sizes occurred, pointing out that these changes may not be important for clinical practice or even re-distributing the load differently on the body for better ergonomics during walking. However, from a public health perspective, cumulative load carriage during a long period of time may be responsible for higher injury risk and distribution compensations in intervention police officers, showing that policymakers should pay more attention to equipment and the way of carrying it on a daily basis.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to the privacy.

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Study 3 (Paper 2)

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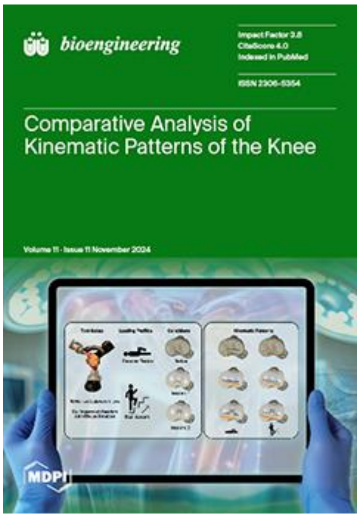

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Spatiotemporal Gait Asymmetries Remain Unaffected by Increased Load Carriage in Professional Intervention Police Officers

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Abstract: Background: Although evidence indicates that load carriage may have an influence on walking patterns, the specific impacts of progressively increased loads on spatial and temporal gait asymmetries remain underexplored. Therefore, the primary aim of this study was to examine whether an increased load carriage had an effect on spatiotemporal gait asymmetries among intervention police officers. Methods: For the purpose of this study, 96 male intervention police officers were recruited and assessed under four load conditions: (i) "No load", (ii) "a 5 kg load", (iii) "a 25 kg load", and (iv) "a 45 kg load". Spatial and temporal gait parameters were measured using a pedobarographic platform (Zebris FDM). The spatial and temporal gait parameters, along with the ground reaction forces beneath different foot regions, were examined. The gait asymmetry for each parameter was calculated using the formula $(x_{right} - x_{left})/0.5 \times (x_{right} + x_{left})*100\%$, where "x" represents the numerical value of each parameter for the left and right sides of the body. Results: The findings indicated no statistically significant differences in the spatiotemporal parameters, nor ground reaction force gait asymmetries between the left and right foot, during walking under a progressively increased load carriage. Additionally, the parameter values for both the left and right sides of the body remained consistent, with a high intercorrelation observed across all of the loading conditions. The gait speed and ground reaction forces, which served as covariates, did not significantly change the spatiotemporal gait asymmetries. Conclusions: In summary, this study demonstrates that an increased load carriage did not lead to a progressive rise in spatiotemporal gait asymmetries in professional intervention police officers. However, further examination using an advanced 3-D gait analysis and an assessment of physiological patterns and adaptations is recommended to identify and confirm the key factors influencing gait asymmetry.

Keywords: specialized populations; standardized load carriage; asymmetry index; differences

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1. Introduction

Load carriage in specialized populations, such as police officers and their branches, has become a significant factor in ensuring protection and survival in high-risk situations [1,2]. Indeed, carrying an external load can provide the necessary resources for daily combat tasks and missions. Although the load has its benefits, the interaction among the individual, the load, and everyday duties and responsibilities is often associated with overall health and the quality of life [3,4]. Numerous studies have investigated the effects of carrying an external load on physiological and biomechanical changes [5–7]. From a physiological perspective, it is expected that heavier loads increase total and active energy expenditure, heart rate, and breathing characteristics [5] due to the greater forces applied on the musculoskeletal system. On the other hand, when it comes to the biomechanical approach, the literature has consistently reported increased flexion in the trunk, hip, and knee, as well as greater extension moments in the knee and ankle regions of the body [7]. However, there are limited data on spatial and temporal gait characteristics, as well as the differences between the sides of the body, in response to progressively heavier external loads; these have yet to be determined.

During bipedal movements, it is normal to observe a certain level of asymmetry, i.e., the inequality between the left and right sides of the body regarding a given parameter. The term "asymmetry" is one of the key factors and a starting point in defining optimal ergonomic efficiency and load positioning on the body. Thus, it is not surprising that it has gained significant attention over the last two decades [8–10]. Indeed, efforts have been made to determine an optimal level of asymmetry for certain physical performance parameters, indicating that a 15% difference between the sides of the body represents an upper threshold [9]. However, these patterns have rarely been observed in the lower extremities, where the literature indicates an increase of up to 50% when carrying heavier loads [8]. The majority of studies have attempted to examine the effects of uneven load carriage on gait biomechanics [10–15]. When carrying an asymmetrical load, previous kinematic analyses have shown that the body naturally increases extensor moments in the hip and knee of the unloaded leg [12]. While examining joint movement during walking, little is known about the relationship between load carriage and spatiotemporal gait asymmetries [11]. The available studies on this topic have shown an increase in gait asymmetry in the ground reaction forces in the medio-lateral direction when heavier loads (up to roughly 20% of the body's weight) are applied [11]. Most recently, a study by Štefan et al. [16] indicated that a 3.5 kg load significantly increased asymmetries in the gait cycle, particularly during the stance, load response, single-limb support, pre-swing, and swing phases and in the step time, compared to the no-load condition in a large sample of police recruits. However, the limitation of the aforementioned study is its exclusive focus on a 3.5 kg load, while the effects of heavier loads on spatiotemporal gait asymmetries remain unexamined.

As the authors of this study are aware, only a handful of studies have attempted to examine the effects of a gradually increasing load carriage on spatiotemporal gait asymmetries. From a practical standpoint, establishing the potential increases in gait asymmetry may result in the even greater eversion and external rotation of the foot, decreases in the step and stride length, and increases in the step and stride time [17], which could lead to injuries and stress fractures [18–20].

Given the critical role of symmetrical gait in performing daily tasks and assignments, it is reasonable to propose that the addition of weight may alter the gait parameters—both temporally and spatially—and have an immediate impact on gait asymmetries. Such disparities in the values between the left and right sides of the body may lead to an altered posture, a decline in function, and an increased risk of injury. However, analyzing how body asymmetry varies under specific loading conditions may provide valuable insights for rearranging or restructuring the current loads to reduce the risk of harmful biomechanical impacts on the body during walking. Lastly, public health policymakers should gain a better understanding of load safety concerns and the potential applications of the findings.

Therefore, the primary aim of this study was to examine whether an increased load carriage had effects on spatiotemporal gait asymmetries among intervention police officers. We hypothesized that gait asymmetries would gradually increase with the greater load carriage.

2. Materials and Methods

2.1. Study Participants

This observational study was conducted among male officers of the Zagreb Police Department Police Intervention Unit, who were anonymously tested. The sample size was calculated using the G*Power (version 3.1.9.7 GmbH) statistical calculator, with a statistical power of 0.80, $p < 0.05$, and a large effect size (0.40), which resulted in a sufficient sample size of N = 80 participants. Considering the dispersal of the sample during the study's implementation, an additional 20% increase was added to the sample size, resulting in N = 96. All of the subjects recruited for the study had been employees of the Police Intervention Unit for at least three years. All of the participants before and during testing were healthy and had no acute chronic illnesses or disabilities that could prevent their participation in the research or lead to the termination of their participation. Before conducting the study, written informed consent was obtained from all of the participants. The study procedure and the testing protocol were approved by the Ethical Committee of the Faculty of Kinesiology and the Police Intervention Department under the Ministry of Internal Affairs of the Republic of Croatia (Ethical code: 511-01-128-23-1).

2.2. Loading Conditions

Each test subject crossed a platform while bearing one of four standard loads recommended by the Ministry of Internal Affairs for intervention police officers. The first load was body-weight-only (referred to as "No load"); the second was a 5 kg load (referred to as "Load 1"), which consisted of a belt with a pistol that was loaded with a full handgun magazine, an additional full handgun magazine, and handcuffs; the mean weight of all of the participants was ±SD = 4.97 ± 0.25 kg. The third load was a 25 kg load (referred to as "Load 2"), which was upgraded with a helmet, a ballistic vest, and a multipurpose baton. The fourth load was a 45 kg load (referred to as "Load 3"), which was upgraded with additional lower extremity protection and a protective gas mask (or ±SD = 45.10 ± 4.33 kg). The load position in the second loading condition was around the participant's hip; for the third load, the helmet was placed on the head, while a ballistic vest was positioned on the chest region, with a multipurpose baton in front of the trunk; for the final, fourth condition, the protection was placed on the knees and arms and a protective gas mask was put behind the head. The sequence of each load was randomized to reduce the impact of a learning effect [21].

2.3. Spatiotemporal Gait Parameters

In order to determine the spatial and temporal parameters, we used the ZEBRIS FDM 1.12. software, which produced data following each attempt. The laptop and software were connected to the platform and set up on the computer, providing immediate data on the gait biomechanics. Spatial and temporal gait parameters were created and pre-programmed within the software. For example, the software recorded spatial measurements such as foot rotation (°), step length (cm), step width (cm), the length of the gait line from first to final foot contact with the ground (mm), and a single limb support line (mm). The degree of foot rotation was determined by measuring the angle between the foot's position and the line connecting both feet. Step length refers to the distance between the heel of one foot and the heel of the other foot, while stride length combines the distances of both steps. The temporal parameters consisted of step durations (s). Step time was defined as the duration between the heel strikes of both feet upon contact with the ground. Gait speed was presented in km/h. Additionally, other temporal parameters were expressed as a percentage of the gait cycle for each foot: the stance phase, which included the load response; mid-stance; pre-swing; and the swing phase. It should be noted that foot rotation, step length, the length of the gait line from initial to final foot contact, the single support line, step time, and the percentage of the gait cycle were measured for both the left and right feet. The ground reaction forces for both feet beneath the forefoot, midfoot, and hindfoot regions were calculated and are presented in N.

2.4. Testing Procedure

In order to measure the spatiotemporal gait parameters, we utilized a pedobarographic platform from the ZEBRIS company, FDM, GmbH, Munich, Germany, which was equipped with 11,264 sensors that were operating at a sampling rate of 100 Hz and had a sensor area of 149 cm × 54.2 cm. This tool is user-friendly for studying gait characteristics, and we followed a testing procedure similar to that used in previous studies [21]. During one day of measuring all four of the levels of equipment for the members of the intervention police, we demonstrated the operation of the system and data collection to the respondents. The method of walking across the platform was explained to everyone, and it was noted that the selection of standard police equipment in different variants was chosen by random selection. Also, none of the respondents had participated in similar research, and, therefore, the effect of learning or adapting to the measurement process was avoided. Each participant carried a randomly selected load across the platform, after which, the procedure of randomly selecting equipment and walking across the platform was repeated. Two custom-built wooden platforms were positioned before and after the testing area to facilitate normal walking. Upon receiving a signal from the researcher, the participants began to move across the platform. Upon reaching the end of the walkway, the participants stopped, turned around, and headed back to their starting position. After measuring each load by randomly selecting each subject, the raw data were automatically entered into the data matrix. An analysis of cross-correlation across all eight trials demonstrated outstanding reliability ($r > 0.90$).

2.5. Statistical Analysis

To assess data normality, we employed the Kolmogorov–Smirnov test. The variables that followed normal distribution were presented as the mean and the standard deviation (SD), and the variables that were not normally distributed were presented as the median and the interquartile range (25th–75th). Asymmetries between the different loading conditions were tested using a one-way repeated measures ANOVA or the Friedman test. If a significant *p*-value was generated, a Bonferroni *post-hoc* test between the loading conditions was applied. The effect size was presented as the partial eta squared, with the following values: "small" (0.01), "medium" (0.06), and "large" (0.14). The gait asymmetries were calculated using the formula proposed by Robinson et al. [22]: $(x_{right} - x_{left})/0.5*(x_{right} + x_{left})*100\%$, where "x" represents a given parameter being calculated. A score of 0 denotes a perfectly symmetrical gait, while an increasing value in either the positive or negative direction indicates a greater asymmetry. Of note, the right side of the body was chosen habitually, and therefore, the values for the left and right sides of the body were entered into the equation. The statistical significance was set at a priori $p \leq 0.05$. All of the analyses were performed using the Statistical Package for Social Sciences (SPSS Inc., Chicago, IL, USA).

3. Results

Basic descriptive statistics and the changes between the left and right sides of the body under different loading conditions in the spatial gait parameters are presented in Table 1. Carrying heavier loads did not result in significant changes to the spatial gait parameters, indicating that the participants maintained similar gait patterns while carrying these loads. Notably, the intercorrelation between the loading conditions for foot rotation, step length, the length of the gait line, and the single limb support line was $r > 0.90$, with the coefficient of variation (CV) being <1.5% within every loading condition, indicating that the participants exhibited similar spatial values and gait biomechanics. When comparing the sides of the body, the mean difference between the left and right foot was not statistically significant, which was also observed for the symmetry index. Heavier loads did not produce a greater asymmetry in the spatial gait parameters, although more substantial changes in asymmetry were observed for the single limb support line, which approached statistical significance. Foot rotation remained the most stable spatial parameter of gait across the different loading conditions.

Table 1. Changes in the spatial gait parameters under the different loading conditions.

Study Variables	Left Foot	Right Foot	Mean Difference	Symmetry Index	*p*	η2
Spatial Gait Parameters	**Mean (SD)**	**Mean (SD)**				
Foot rotation (°) *						
No load	8.3 (4.9–11.4)	10.1 (7.4–14.7)	1.8	0.22		
Load 1	7.8 (4.9–11.4)	9.9 (6.1–14.4)	2.1	0.27		
Load 2	8.6 (5.2–11.6)	10.3 (7.7–14.0)	1.7	0.20		
Load 3	8.1 (5.3–10.7)	9.9 (6.7–13.9)	1.8	0.22	0.908	0.002
Step length (cm)						
No load	68.5 (5.6)	67.6 (5.9)	0.9	−0.02		
Load 1	68.7 (6.3)	68.7 (5.8)	0.0	0.00		
Load 2	68.5 (6.3)	68.5 (6.0)	0.0	0.00		
Load 3	68.9 (6.4)	69.0 (6.2)	0.1	0.00	0.424	0.009
Step width (cm)						
No load	15.3 (2.9)		/	/		
Load 1	15.4 (2.7)		/	/		
Load 2	15.6 (2.8)		/	/		
Load 3	15.7 (3.0)		/	/	0.759	0.003
Length of gait line (mm)						
No load	239.1 (26.3)	242.4 (18.2)	3.3	0.01		
Load 1	242.4 (22.1)	239.5 (23.6)	2.9	−0.01		
Load 2	245.1 (17.9)	240.9 (24.9)	4.2	−0.02		
Load 3	242.7 (22.9)	243.3 (19.4)	0.6	0.01	0.160	0.014
Single limb support line (mm)						
No load	121.6 (21.3)	125.7 (13.0)	4.1	0.03		
Load 1	127.1 (20.4)	122.0 (15.4)	5.1	−0.04		
Load 2	124.8 (13.9)	120.6 (17.2)	4.2	−0.03		
Load 3	123.5 (13.8)	120.7 (14.6)	2.8	−0.02	0.090	0.020

* denotes using median and interquartile range (25th–75th percentile); $p < 0.05$.

Changes in the temporal gait parameters are shown in Table 2. Similarly to the spatial gait parameters, no significant changes in any of the measured parameters were observed, irrespective of the side of the body. The intercorrelation coefficient was also extremely high ($r > 0.90$, CV < 2.0%) within each side of the body. When comparing the sides of the body, the mean difference between the left and the right foot was not statistically significant, which was also observed for the symmetry index. Additionally, heavier loads did not produce a greater asymmetry in the temporal gait parameters, although more substantial changes in asymmetry were observed for the stance, load response, and swing phases of the gait.

Table 2. Changes in the temporal gait parameters under the different loading conditions.

Study Variables	Left Foot	Right Foot	Mean Difference	Symmetry Index	p	η2
Temporal Gait Parameters	**Mean (SD)**	**Mean (SD)**				
Step time (s)						
No load	0.55 (0.04)	0.55 (0.04)	0.00	0.00		
Load 1	0.54 (0.04)	0.55 (0.06)	−0.01	0.02		
Load 2	0.54 (0.04)	0.55 (0.05)	−0.01	0.02		
Load 3	0.53 (0.04)	0.54 (0.04)	−0.01	0.02	0.576	0.006
Stance phase (%)						
No load	62.1 (2.1)	62.3 (1.7)	0.02	0.00		
Load 1	62.3 (1.9)	61.6 (3.1)	−0.7	−0.01		
Load 2	62.7 (1.8)	62.5 (1.9)	−0.2	0.00		
Load 3	62.8 (1.9)	62.5 (1.9)	−0.3	−0.01	0.140	0.017
Load response (%)						
No load	12.3 (1.5)	12.0 (1.9)	−0.3	−0.02		
Load 1	11.8 (1.6)	12.1 (1.5)	0.3	0.03		
Load 2	12.4 (1.9)	12.7 (2.0)	0.3	0.02		
Load 3	12.6 (1.5)	12.7 (2.2)	0.1	0.01	0.135	0.017
Mid-stance (%)						
No load	37.8 (1.7)	37.5 (3.9)	−0.3	−0.01		
Load 1	38.4 (3.0)	37.5 (2.0)	−0.9	−0.02		
Load 2	37.7 (2.3)	37.2 (2.0)	−0.5	−0.01		
Load 3	37.5 (2.1)	37.2 (2.0)	−0.3	−0.01	0.874	0.002
Pre-swing (%)						
No load	12.1 (1.9)	12.3 (1.5)	0.2	0.02		
Load 1	12.3 (1.6)	12.2 (2.0)	−0.1	−0.01		
Load 2	12.5 (2.0)	12.9 (1.8)	0.4	0.03		
Load 3	12.7 (2.1)	12.7 (1.4)	0.0	0.00	0.318	0.011
Swing phase (%)						
No load	37.9 (2.1)	37.7 (1.7)	−0.2	−0.01		
Load 1	37.6 (1.5)	38.3 (2.9)	0.7	0.02		
Load 2	37.3 (1.8)	37.5 (1.9)	0.2	0.01		
Load 3	37.2 (1.9)	37.5 (1.9)	0.2	0.01	0.161	0.016
Gait speed (km/h)						
No load	4.4 (0.5)		/	/		
Load 1	4.6 (0.5)		/	/		
Load 2	4.6 (0.6)		/	/		
Load 3	4.7 (0.6)		/	/	0.064	0.022

$p < 0.05$.

Table 3 shows changes in the ground reaction force asymmetries following the different loading conditions. The findings indicated no significant changes in the force asymmetries beneath the different foot regions when a gradually heavier load was added. Of note, when each model was adjusted for gait speed and ground reaction force, similar patterns and effect sizes remained.

Table 3. Changes in the ground reaction force asymmetries under the different loading conditions.

Study Variables	Left Foot	Right Foot	Mean Difference	Symmetry Index	*p*	η2
Temporal Gait Parameters	**Mean (SD)**	**Mean (SD)**				
Forefoot (N)						
No load	852.3 (109.9)	865.6 (113.8)	13.3	0.01		
Load 1	873.0 (166.0)	893.0 (126.7)	20.0	1.79		
Load 2	960.6 (115.1)	967.6 (115.2)	7.0	0.01		
Load 3	978.4 (108.9)	984.4 (114.2)	6.0	0.01	0.151	0.016
Midfoot (N)						
No load	170.6 (70.3)	173.9 (68.7)	3.3	0.08		
Load 1	170.0 (74.2)	178.1 (75.4)	8.1	0.27		
Load 2	187.8 (75.4)	202.1 (81.4)	14.3	0.13		
Load 3	191.9 (82.6)	206.6 (82.0)	14.7	0.17	0.251	0.013
Hindfoot (N)						
No load	588.6 (89.9)	568.1 (84.5)	−20.5	−0.04		
Load 1	609.5 (82.0)	580.5 (94.0)	−29.0	−0.06		
Load 2	651.3 (86.6)	617.4 (87.3)	33.9	−0.06		
Load 3	662.2 (90.4)	636.6 (95.1)	−25.6	−0.03	0.323	0.011

4. Discussion

The main purpose of this study was to examine the effects of an increased load carriage on spatiotemporal gait asymmetries in intervention police officers. The findings of the study indicate no significant differences between the left and right sides of the body, nor any expected increases in the spatial and temporal gait asymmetries following the addition of a gradually heavier load.

To the authors' knowledge, thus far, no studies have explored changes in spatial and temporal gait asymmetries under different loading conditions in intervention police officers. One common approach in detecting gait imbalances typically involves measuring the ground reaction forces between the feet and the ground during a stance position [11,23]. It has been shown that approximately two-thirds of the participants exhibited greater foot asymmetry in the transversal and frontal planes, compared to when carrying no load. However, limited data exist on examining the same patterns during walking. When comparing the sides of the body regarding the ground reaction forces during walking, a study by Zhang et al. [11] found that heavier loads led to a greater asymmetry index, but the same load did not affect both feet equally.

Although we hypothesized that heavier external loads would gradually produce greater spatial and temporal gait asymmetries, we did not observe such findings. One potential mechanism could be attributed to a learning effect and the participants' experience in carrying such loads on a daily basis. For example, of the three loads studied in this research, the first is often carried throughout the day, typically for 8 to 10 h. The second level of equipment is commonly used in urban situations (such as maintaining order at soccer matches, etc.), which require a higher level of risk and an additional level of protection. On average, such equipment is worn two to three times a week for approximately 12 h. The third level of equipment is intended for tasks involving the control of immigrants, terrorist attacks, etc. Intervention police officers wear this equipment for durations of 10 days to 2 weeks, for approximately 10 to 12 h per day. Given the regular use of all of the levels of equipment and the extensive service experience of the intervention police officers, it is reasonable to assume that they have adapted to wearing heavier official gear, which does not significantly alter their walking patterns, particularly in the area of spatial and temporal parameters. Although we did not perform a 3-D analysis of the upper extremities, it is speculated that certain adjustments were made in the inertial patterns of the musculoskeletal system due to the load placement on the body, which may have limited the natural arm swing during walking.

Despite non-significant changes in asymmetry with heavier loads, the evidence implies that the trunk tends to lean away from the side carrying the load, suggesting that motor control responses to external loads may be related to load-carrying strategies and characteristics. Differences in posture between the left and right sides are influenced by the dominant side of the body, which directly affects gait asymmetry throughout the kinetic chain. Although asymmetry often occurs because of variations in stride length or cadence/walking speed [5], the findings of this study did not reveal significant asymmetry changes in these parameters. To overcome this problem, we adjusted for gait speed and ground reaction forces, which may interact with spatial and temporal gait parameters following different loading conditions. However, we found no significant interaction effect of the aforementioned covariates in any of the models, indicating that neither gait speed nor ground reaction forces significantly affected the gait with the heavier loads. The reason for this result may be the relatively homogenous sample of intervention police officers with similar biomechanical gait patterns, constitutions, and load weights, which potentially mimic the possible effect of other habitual factors (like gait speed or ground reaction force) on gait. The second mechanism may be attributed to physiological, rather than biomechanical, responses to heavier loads, as confirmed and highlighted in other studies [24,25]. From a biomechanical perspective, carrying a heavy load near the center of gravity represents the most efficient method, as it minimizes energy consumption [26]. Physiologically, previous studies have shown that an increase in load of 15% may gradually increase both resting and active energy consumption by 5–6%, due to the trunk being positioned more forward compared to the no-load condition [25].

Despite the negative findings, this study is the first to investigate both spatial and temporal gait parameters in a representative sample of intervention police officers. Although the load increments did not affect the gait patterns, the findings of this study may have practical implications for examining the movement patterns of the arms, trunk, hips, and knees, providing more detailed information regarding the various angles and angular velocity properties of the joints. Additionally, the non-significant biomechanical discrepancies in spatial and temporal gait parameters should be interpreted through the lens of physiological mechanisms and 3-D kinematic and kinetic analyses, which would offer better insight into the factors contributing to these patterns.

This study has several limitations. Due to its cross-sectional design, we cannot determine causal relationships regarding the asymmetries, which limits the generalizability of the findings to police recruits, who have not yet gained sufficient experience with police tasks and equipment. Second, we only examined spatiotemporal gait parameters, while 3-D kinematic and electromyography systems would have provided additional insights into the increased gait asymmetries following the application of "a 3.5 kg/7.7 lb load". Third, we did not assess biological and physiological parameters, which may clarify the relationship between the dynamic foot parameters and load carriage. Additionally, we did not gather data regarding injury history or the methods of load carriage, which limits our ability to draw practical implications for repositioning load items and exploring the potential effects of load carriage on injury incidence. Fifth, previous studies have shown different systematic evaluations of the feature encoding techniques of sensory data [27], like codebook-based and deep learning-based approaches. However, the same study confirmed that handcrafted feature-based techniques achieved a high recognition rate of approximately 96.0% for the recognition results of different human movements, showing such approaches to be as relevant as other new and more sophisticated techniques in presenting the data [27]. Finally, the participants walked barefoot over the pressure platform, which may have affected their gait patterns. Therefore, future research that is aimed at examining gait asymmetries during load carriage should focus on longitudinal study designs and comprehensive physiological and biomechanical analyses, as well as load- and injury-related characteristics. These factors may be crucial in limiting the negative effects of load carriage on the gait.

5. Practical Implications

Insignificant differences between the asymmetry of the spatial and temporal parameters of the gait using heavier equipment indicate how the members of the intervention police, as subjects of this research, achieved an established biomechanical pattern of movement in dynamic conditions. Namely, it is to be expected that asymmetries between the right and left side of the body will gradually increase, which was not the case in this study. From a practical point of view, it was determined that the different levels of equipment did not significantly affect asymmetry, which can be explained by learned motor control and ways of carrying the load itself during training or special tasks. However, there is still an unknown regarding the biomechanical differences between the right and left side of the body during long-term walking or running, which we could not confirm in this research. According to Knapik et al. [2] and Boffey et al. [5], the physiological component of carrying an external load can be more influenced than the biomechanical one, especially in populations that are subjected to the same or similar loads on a daily basis. Namely, it has been shown that the consumption of energy and oxygen increases physiologically during a heavy load, and the state of fatigue increases significantly [2,5]. On the other hand, fatigue could also be measured by the time spent walking across the platform with different loads, but due to the nature of the data collection and the daily activities of the emergency police personnel, this was not possible. Nevertheless, walking at a normal and habitual pace with heavier equipment did not affect the biomechanics of the lower extremities, but other components, mentioned in the Discussion Section, need to be further explored.

6. Conclusions

In summary, this study demonstrates that a heavier load carriage did not progressively increase spatial and temporal gait asymmetries in professional intervention police officers. Health and law enforcement personnel can benefit from these findings, as carrying heavy loads does not adversely affect body equilibrium or the disproportion of the gait between the left and the right sides of the body. However, other bodily functions, such as physiological changes during walking with heavier loads, should be examined and integrated into the system to identify the most significant factors influencing gait asymmetry.

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Informed Consent Statement: All of the subjects gave their informed consent for inclusion before they participated in the study.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

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13. BIOGRAPHY OF THE AUTHOR AND LIST OF WORKS

Davor Rožac was born in 1975 in Osijek (Croatia), where he attended the elementary school (Mladost Osijek) and high school (Agricultural and Veterinary high school Osijek XI, thereby obtaining the title of Veterinary Technician). He graduated from the Faculty of Physical Education in 2011. From 2011, he works as an Expert Associate at the Faculty of Kinesiology in Zagreb in the subjects of Judo and Martial Arts. From 1984 to 2009, he was a successful competitor in judo and ju-jitsu and he won a number of medals and titles at international tournaments. In 2007 and 2009, he won gold medals on Denis Survival Ju-Jitsu Chamionship in Israel, and he was promoted to black belt 6th DAN in ju-jitsu. After finishing his competitive career, he worked as a coach in several judo and ju-jitsu clubs. He also trains judo and martial arts children with physical and mental disabilities, as well as blind and visually impaired people. From 2018 he is a coach in the Croatian Paralympic judo team. He is a founder of Bukyo Ryu Ju-Jitsu, Judo Club Budokan, Judo Club Koprivnica, Triathlon Club Zrinski, DSR Omega, DSR Underground, Gladius Fidei d.o.o. and several other successful sports clubs and companies.

The list of publicly published works is as follows:

1. **Rožac, D.**, Kasović, M., & Knjaz, D. (2024). Spatiotemporal Gait Asymmetries Remain Unaffected by Increased Load Carriage in Professional Intervention Police Officers. *Bioengineering*, *11*(11), 1140. https://doi.org/10.3390/bioengineering11111140
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