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Load Carriage and Changes in Spatiotemporal and Kinetic Biomechanical Foot Parameters during Quiet Stance in a Large Sample of Police Recruits

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Abstract: Background: Little evidence has been provided regarding the effects of carrying standardized load equipment and foot parameters during quiet standing. Therefore, the main purpose of the study was to examine whether a load carriage might impact static foot parameters in police recruits. Methods: Eight hundred and forty-five police recruits (27.9% women) were tested in 'no load' vs. standardized '3.5 kg load' conditions. Foot characteristics during standing were assessed with the Zebris FDM pedobarographic pressure platform. Results: Carrying a 3.5 kg load significantly increased the 95% confidence ellipse area (Δ = 15.0%, $p = 0.009$), the center of pressure path length (Δ = 3.3%, $p = 0.023$) and average velocity (Δ = 11.1%, $p = 0.014$), the length of the minor axis (Δ = 8.2%, $p < 0.009$) and the deviation in the X (Δ = 12.4%, $p = 0.005$) and Y (Δ = 50.0%, $p < 0.001$) axes. For relative ground reaction forces, a significant increase in the left forefoot (Δ = 2.0%, $p = 0.002$) and a decrease in the left hindfoot (Δ = −2.0%, $p = 0.002$) were shown. No significant changes in relative ground reaction forces beneath the forefoot and hindfoot regions for the right foot were observed ($p > 0.05$). Conclusions: 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

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1. Introduction

Load carriage is an essential part of training and on-duty protocol tasks for special populations, including the military [1,2] and police [3]. Although important, it has been observed that such a load may impact the musculoskeletal system, causing an increased risk of lower limb injury [4] and decreased physical performance [5,6] Moreover, recent studies have observed a negative trend in load weight, often surpassing the recommended level of 45% body mass [7,8]

When carrying heavy loads, gait and posture characteristics often tend to change and adapt [9]. 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 and alternatively causing alternations in body control [10]. The majority of previous evidence has tried to examine the effects of load carriage on foot parameters during gait; however, little evidence has been provided regarding carrying heavy loads and foot stability during a quiet stance [1,11–13]. By carrying a load, a physiological component of increased energy cost and fatigue has often been observed, increasing the risk of injuries and strains [14,15]. For quiet standing, deviations in the center of pressure may be able to predict future risks of injury and postural instability [16], especially in the lower extremities [17]. Both cross-sectional [18] and longitudinal [8,19] studies have shown that different load distributions may have even larger negative effects and can increase the level of asymmetry. Studies conducted during quiet standing have concluded that heavier loads increase the center of pressure velocity and contact area between the foot and the ground, directly affecting ground reaction forces beneath different foot regions [1,20].

The population of police officers needs to be at a high level of preparation [21]. Their primary role includes serving and protecting civilians against crime, and they are engaged in high-risk situations [21]. However, by carrying an uneven load for a long period of time, one could expect significant biomechanical gait changes, especially in a standing position. A unilateral load may affect postural sway, which occurs by shifting the body mass center away from the actual center and leaning forward, producing greater forces beneath the different foot regions [1]. Police recruits encounter carrying a specific external load for the first time, which may have negative effects on their body posture and related biomechanical parameters. Such loads may be responsible for pain and discomfort and a few compensatory mechanisms, especially in the contralateral directions [20]. Since relatively little is known on this topic, it is necessary to examine spatiotemporal foot changes and relative ground reaction forces during quiet standing following a standardized load carriage. By examining such changes, policymakers would be able to act towards re-positioning and re-designing police equipment. The intention behind newly developed equipment would be to increase the possibility of being more efficient in the field during high-risk situations.

Therefore, the main purpose of the study was to examine differences in foot characteristics while standing still under two conditions: (i) 'no load' and (ii) 'a 3.5 kg load'. We hypothesized that heavier loads would exhibit greater biomechanical foot changes and impaired balance compared to the 'no load' condition.

2. Methods

2.1. Study Participants

In this cross-sectional study, we recruited men and women >18 years of age who were part of the one-year academy training program aiming to become a part of the Croatian police service. The training program consists of monitoring and improving health-related physical fitness and learning everyday specific tasks and duties on the field. The technical and tactical parts of the program include handling a gun and behaving in high-risk situations, which are often accompanied by psychological preparation and an assessment of the environment. All these tasks are completed while carrying standardized police equipment on a daily basis. In general, a police academy recruits between 750 and 1000 every year. From December 2023 till the first half of February 2024, when the study was conducted, 900 police recruits were examined and selected to participate in the study. Since the academies' rules and regulations state that all recruits need to be without acute and chronic locomotor or psychological diseases, all eligible participants entered the study at the first stage. Of these, 55 were excluded due to illness or a musculoskeletal injury obtained during the training process. Thus, our final sample included in further analyses was based on 845 police recruits (age mean ± SD = 21.3 ± 2.1 years; height = 176.2 ± 12.6 cm; weight = 74.2 ± 11.8 kg; body mass index = 23.9 ± 3.1 kg/m^2; 27.9% women) (Figure 1). All participants had been given information regarding the general and specific aims, hypotheses, benefits and potential risks. All the procedures were anonymous and in accordance with the Declaration of Helsinki [22]. Furthermore, all participants gave written informed consent to participate in the study. This study was approved by the Ministry of Internal Affairs and police academy 'Josip Jović' and the Ethical Committee of the Faculty of Kinesiology, University of Zagreb, Croatia (ethical code number: 511-01-128-23-1).

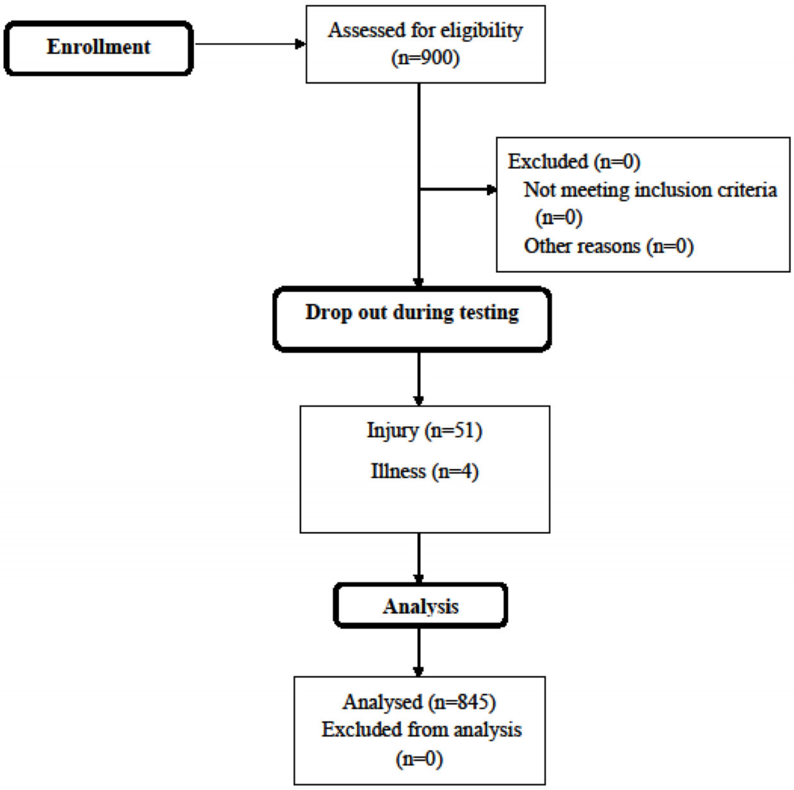

Figure 1. Flow chart diagram of participants' enrolment, randomization and final analysis.

2.2. Load Carriage

A standardized police load often includes a bulletproof vest and a belt, accompanied by a full handgun and an additional handgun magazine consisting of 10 bullets, handcuffs and a nightstick. Based on the nature of this study and the recruitment of future police officers, the training protocol specifically dictates that they only need to have a standardized belt with the aforementioned equipment for physical and mental demands during the day, and the vest is often dismissed due to many task assignments being carried out with the upper body. Although previous evidence has examined the effects of a full load carriage on biomechanical foot parameters [1], for the purpose of this study, we selected standard police equipment carried during police training approximately 10–12 h per day, which consisted of a belt (≈0.5 kg), a gun with a full handgun's magazine (a short barrel HS pistol, ≈1.5 kg), an additional full handgun's magazine (≈0.5 kg), a nightstick (≈0.8 kg) and handcuffs (≈0.2 kg). In total, the whole equipment without a police suit weighs ≈3.5 kg.

2.3. Static Foot Parameters

Measurements of all participants 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 weight. Ground reaction forces (absolute in N and relative in %) were measured. Each participant stepped on the Zebris medical platform for the measurement of pedobarographic plantar characteristics (type FDM 1.5). The Zebris platform uses 11.264 microsensors, 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 still [23]. The Zebris platform was connected via a USB cable to an external unit (laptop). The data were gathered in real time using WinFDM R1.0.0 software for extraction and calculation. Measurement values could be additionally exported in the form of text, pictures, and videos while simultaneously comparing the data from both feet. The capacity of the sensor technology was based on the calibration of every single sensor automatically integrated into the platform. The task was to stand on the platform and maintain a calm position, with arms relaxed by the body and looking straight forward. After 15 s 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 minor axis (X) (mm), (v) length of major axis (Y) (mm), (vi) deviation X, (vii) deviation Y and (viii) the angle between Y and the major axis (°). Specifically, the left and right points under each foot represent the respective area of the CoPs surrounded by the 95% CI. Inside the 95% CI area, the projection of the CoP and its velocity with an appropriate path length during a quiet stance is displayed. The length of the minor axis denotes the medio-lateral direction, while the length of the major axis represents the antero-posterior direction, while the angle between the Y axis and the global y axis is described as the angle between the major axis (Y) and the global y axis, pointing along the longitudinal line of the platform. For ground reaction forces, the software generated the data for the relative forces distributed under the forefoot and backfoot regions of the foot, as well as for the total foot (%). The ideal load distribution is often considered to be 50–50% between the right and left standing surfaces, and the distribution load between the forefoot and heel is suggested to be 33% (1/3) on the forefoot, compared to 66% (2/3) on the heel. Of note, the vertical component of the ground reaction forces was collected and analyzed. Along with biomechanical static foot parameters, in addition, we measured height and weight with standardized equipment (Seca stadiometer and digital scale with a precision of 0.1 cm and 0.1 kg). Height was measured in an upright position while the head was positioned in a neutral position and the vertex was the highest point of the contact. The stadiometer was placed behind the back region from the feet to the vertex, and height was measured in centimeters. To assess weight, each participant stood in a light T-shirt and shorts on the digital scale, which showed each weight in kilograms. Accordingly, body mass index [(weight/kg)/(height/m)^2] was calculated to examine nutritional status.

2.4. Statistical Analysis

The Kolmogorov–Smirnov test to examine whether the data were significantly different from the Gauss distribution was used to assess the normality of the distribution. Since all the study variables were not normally distributed, i.e., were significantly different from the normal distribution, the basic descriptive statistics of the study participants were presented as the median with the interquartile range (25th percentile and 75th percentile). Changes in the biomechanical foot parameters during quiet standing with 'no load' vs. 'a 3.5 kg load' were tested using the non-parametric Wilcoxon signed rank test for dependent samples, where differences were examined in one sample during the two measuring conditions: 'no load' vs. a '3.5 kg' load. Cohen D effect sizes of 0.2, 0.5 and 0.8 (small, medium and high) were used to assess the magnitude of differences between 'no load' vs. 'a 3.5 kg load' [24]. Although we tested spatiotemporal and kinetic foot parameters for both men and women, a preliminary analysis showed that there were no significant differences in the changes between them (p = 0.230–0.768), so further analyses were based on the total sample. All statistical analyses were performed using the Statistical Packages for Social Sciences (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

The basic descriptive statistics of the study participants are presented in Table 1. Men were taller, heavier and had higher body mass index values compared to women.

The initial sample of 845 individuals recruited at the beginning met all the inclusion and exclusion criteria. and no individual dropped out of the study during the assessment. In total, further analyses were based on 845 police recruits. The changes in the static foot parameters under the different loading conditions are presented in Table 2. When carrying a '3.5 kg load', the participants exhibited significantly higher values in the confidence ellipse area (mean difference = 19.0 mm^2; ES = 0.33), the center of pressure path length (mean difference = 3.0 mm; ES = 0.11) and average velocity (mean difference =10 mm/s; ES = 0.27), the length of the minor axis (mean difference = 0.7 mm; ES = 0.25), and the deviations in X (mean difference = 1.6 mm; ES = 0.24) and Y (mean difference = 1.8 mm; ES = 0.43). Insignificant spatiotemporal changes in the length of the major axis and the angle between the Y and major axes were observed. For the relative ground reaction forces beneath the different foot regions, carrying a '3.5 kg load' significantly increased the relative average force beneath the left forefoot region (ES = 0.15), while a decrease in the relative average force beneath the left hindfoot was shown (ES = 015). Interestingly, no significant main changes in the right forefoot or hindfoot were observed ($p > 0.05$).

Table 1. Basic descriptive statistics of the study participants.

Study Variables	Total (N = 845)	Men (N = 609)	Women (N = 236)	ES	*p*-Value
Age (years)	21.3 ± 2.1	21.1 ± 1.9	21.4 ± 2.4	0.02	0.987
Height (centimeters)	176.2 ± 12.6	181.3 ± 10.4	171.9 ± 11.5	0.90	<0.001
Weight (kilograms)	74.2 ± 11.8	82.6 ± 13.4	68.7 ± 10.9	1.04	<0.001
Body mass index (kg/m^2)	23.9 ± 3.1	25.2 ± 3.6	23.2 ± 2.9	0.56	<0.001

Table 2. Basic descriptive statistics and changes in biomechanical static foot parameters under the different loading conditions in police recruits.

Study Variables	'No Load'	'A 3.5-kg Load'	Δ (%)	ES	*p*-Value
Static Parameters	**Median (25th–75th)**	**Median (25th–75th)**			
Confidence ellipse area (mm^2)	127.0 (76.5–236.0)	146.0 (85.0–253.0)	15.0%	0.33	0.009
Center of pressure path length (mm)	91.0 (64.5–127.0)	94.0 (69.0–134.0)	3.3%	0.11	0.023
Center of pressure average velocity (mm/s)	9.0 (6.0–13.0)	10.0 (7.0–13.0)	11.1%	0.27	0.014
Length of minor axis (mm)	8.5 (6.3–12.0)	9.2 (6.9–12.5)	8.2%	0.25	<0.001
Length of major axis (mm)	19.4 (14.6–27.2)	20.3 (15.2–26.9)	4.6%	0.09	0.201
Angle btw. Y and major axis (°)	77.8 (66.4–84.4)	77.0 (62.8–84.7)	−1.0%	0.02	0.225
Deviation X (mm)	12.9 (4.0–23.5)	14.5 (2.0–26.2)	12.4%	0.24	0.005
Deviation Y (mm)	−3.6 (−9.95–3.10)	−1.8 (−9.7–5.6)	50.0%	0.43	<0.001
Relative average force—left forefoot (%)	51.0 (47.0–55.0)	52.0 (48.0–56.0)	2.0%	0.15	0.002
Relative average force—left hindfoot (%)	49.0 (45.0–53.0)	48.0 (44.0–52.0)	−2.0%	0.15	0.002
Relative average force—left total (%)	47.0 (40.0–53.0)	46.0 (39.0–53.0)	−2.1%	0.10	0.345
Relative average force—right forefoot (%)	50.0 (46.0–54.0)	50.0 (45.0–55.0)	0.0%	0.01	0.714
Relative average force—right hindfoot (%)	50.0 (46.0–54.0)	50.0 (45.0–55.0)	0.0%	0.01	0.578
Relative average force—right total (%)	53.0 (47.0–60.0)	54.0 (47.0–61.0)	1.9%	0.12	0.285

$p < 0.05$.

4. Discussion

The main purpose of the study was to examine changes in foot characteristics during quiet standing under the following two conditions: (i) 'no load' vs. (ii) a '3.5 kg load'. The main findings of the study are as follows: (a) when carrying a '3.5 kg load', significant increases in the confidence ellipse area, the center of pressure path length and average velocity, the length of the minor axis, and the deviation in X and Y are observed and (b) significant changes in the relative ground reaction forces beneath the left forefoot and hindfoot regions are shown.

To the best of the authors' knowledge, this is the first study aiming to investigate the effects of a '3.5 kg load' on spatiotemporal and kinetic foot parameters during quiet standing. Previous evidence has confirmed that heavier loads may impact several foot characteristics during a quiet stance, including increases in the mean postural sway during a double stance, the center of pressure path length, the average velocity and the lengths of the minor and major axes with a decrease in the angle between the Y and major axes [11,20,25]. Evidence suggests that load carriages produce greater foot changes and affect body sway during standing, which directly disrupts the body's center of mass, causing it to shift from a point of stability to the boundaries of the base of support. In that way, one could expect that a loss of balance in the medio-lateral and anterior-posterior directions is essential to maintaining an upright stance by using ankle and hip compensation movements [12,20]. 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 an external load, the resulting body motion is counterbalanced by one of the strategies which increase postural sway. Along with the benefits of carrying a load in high-risk situations, a contra-productive effect on the ability to maintain upright control and posture often occurs. Certain compensations are required to carry an external load in terms of body movement patterns moving away from equilibrium and changing the structure of the postural sway movements [26,27]. Heavy loads have been shown to increase injury incidence and negatively affect physical performance [4]. With increased energy costs and repetitive force requirements, biomechanical changes in spinal loading, gait patterns and ground reaction forces may increase the risk of injuries, with the knees, ankles and feet being the most affected body parts [7,8]. Due to constant load and bone remodeling imbalances, repetitive bone loadings often lead to stress fractures connected to neurological injuries [28]. Indeed, previous evidence suggests that a previous injury is a risk factor for future injury, pointing out that individuals who have experienced a work-related injury are more prone to future injury and ambulatory treatment [29]. Another risk factor for even more foot deviations is load distribution. Although we were unable to test different load distributions and their impacts 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 the contributions of hip muscles to forward progression [30].

This is one of the first studies examining the effects of a '3.5 kg' load on spatiotemporal and kinetic foot parameters during a quiet stance in a large sample of police recruits. Indeed, carrying heavy loads and determining their impact on biomechanical changes during walking [1] and standing [20] have been a topic of interest in the special populations of the military and police, pointing out that a heavy load may have a negative impact on performance and overall body posture during completing everyday tasks and duties. On the other hand, the necessity of carrying equipment represents a crucial component of survival in often high-risk operations and situations. To overcome the reverse health benefits of load carriages, policymakers are keen to develop and implement differently re-positioned and managed loads on the body. For example, studies have shown that when carrying a standardized backpack, it should be placed tightly close to the center of mass to decrease strain in the anterior or lateral positions during walking or standing [5]. Among Croatian police, a handgun is often carried on one side of the hip, which constantly disables the arm of that side of the body from swinging naturally. Although we did not examine the 3D kinematics of the upper body extremities, we observed that the 'affected' arm, both during walking and standing, is positioned further away from the trunk because of the position of the handgun, leading the participants to lean to the other side and have an increased risk of scoliosis and numbness in the neck area and upper extremities. Indeed, previous evidence has shown that a unilateral load carriage is more hazardous to the musculoskeletal body system compared to a bilateral load carriage in terms of increased muscle activity and greater spinal shear [31]. Such a load being carried for a long period of time may impact back curvature positions, leading to scoliotic posture [31]. Biomechanical analyses conducted in individuals carrying a unilateral load have demonstrated that the trunk often bends towards the unloaded side of the body, causing greater hip, knee and ankle joint moments during the single stance phase [32]. Two-way adaptations have been proposed by Huang et al. [33], where the active trunk flexions towards the contralateral side of the body, while the hip adducts greatly lean towards the ipsilateral side of the body. The latter relies on the fact that the trunk is somewhat pulled sideward on the ipsilateral side of the body, while the hip goes in the opposite direction towards the contralateral side. Huang et al. [33] showed that of the two adaptations, the pulling force produced while carrying a unilateral load caused the trunk to bend more to the ipsilateral than the contralateral side of the body. However, the load carried in these studies was much greater ($\geq$10% body weight) compared to the 3.5 kg load (approximately 4% to 5% body weight) used in this study. One potential mechanism of re-positioning the handgun is moving it to the lateral side of the thigh area, which could restrict the arms from moving swiftly and repeatedly. Unfortunately, the policy in Croatia still states that a standardized police load needs to be worn around the hips, and the additional effect of carrying such a load for between 10 and 12 h per day may cause hazardous health-related outcomes in the future. Thus, special interventions and strategies aiming to change the ergonomics and design of police equipment should be implemented within the police system in order to adequately protect one's postural characteristics and utilize energy expenditure during walking and standing [5].

This study has several limitations. First, by using a cross-sectional design, we were unable to examine the longitudinal changes in static foot parameters while carrying heavy loads. Second, we tested healthy men and women between the ages of 18 and 24 who were free of any medical conditions and who could apparently handle body compensations more effectively while carrying equipment compared to more experienced police officers with different socio-demographic backgrounds. Third, we did not collect biological and physiological parameters, which may help to assess the link between static foot parameters and different loading conditions. Also, no data regarding injury history or how the load was carried were collected, limiting the possibility of expanding our findings to practical implications towards re-positioning items and exploring the potential effects of load carriages on the incidence of injuries. Moreover, no 3D kinematic and muscle activation systems were assessed, limiting our findings to be observed only through a pressure platform and a vertical projection of ground reaction forces. Finally, the participants walked barefoot over the pressure platform, potentially limiting the generalizability and applicability of the findings to the different everyday tasks of other populations in police-related fields or military personnel. Based on the aforementioned limitations, future longitudinal studies 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.

5. Conclusions

In summary, this is the first study examining changes in spatiotemporal and kinetic static foot parameters while carrying a '3.5 kg load' vs. 'no load'. The findings of the study showed that an increased external load might increase the confidence ellipse area, the center of pressure path length and average velocity, the length of the minor axis, the deviations in X and Y, and the forefoot and hindfoot regions of the left foot, while the ground reaction forces beneath the right foot regions were not impacted by the load. Therefore, spatial and temporal parameters during quiet standing may be more prone to changes following an external load compared to ground reaction forces, pointing out that future research should focus on foot characteristics rather than forces being generated beneath the feet. The results of this study are important due to the problem of wearing standard police equipment and its influence on spatiotemporal and kinetic parameters during standing. We believe that wearing the same equipment while walking would result in even greater negative biomechanical changes to the feet and thus to the entire body, and future research must concentrate on studying the same effects during standardized tasks and in different physiological states, such as fatigue or sleep deprivation.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Ethics Committee of the Ministry of Internal Affairs and police academy 'Josip Jović' and the Ethical Committee of the Faculty of Kinesiology, University of Zagreb, Croatia (ethical code number: 511-01-128-23-1, date: 3 July 2023).

Informed Consent Statement: All 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.

Conflicts of Interest: The authors declare no conflict of interest.

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