A carried military load increases the impact force and time of a front kick but reduces the peak velocity of the hip and shoulder of the kicking leg

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Authors' Contribution:
- **A** Study Design
- **B** Data Collection
- **C** Statistical Analysis
- **D** Manuscript Preparation
- **E** Funds Collection

Received: 30 January 2020; **Accepted:** 25 February 2020; **Published online:** 17 March 2020

AoBID: 13293

Abstract

Background and Study Aim: Wearing of protective equipment and a backpack is a crucial factor that influences velocity and dynamic forces during the front kick, which is largely described in unloaded conditions. Therefore, the aim of this study was the knowledge about the effects of wearing a ballistic vest and backpack on the peak velocity and dynamic forces during the front kick.

Material and Methods: Twenty-five male soldiers (27.7 ±7.2 yr, 83.8 ±6.1 kg, 180.5 ±6.5 cm) performed six individual front kicks with no carried load (NL) and with 30-kg loads composed of military equipment (WL) (boots and rifle = 3 kg, ballistic vest =12 kg and backpack = 15 kg). The 3D kinematics and kinetics were used to estimate the kick velocity and dynamic forces of the front kicks. Peak force (N), impulse (N·s), time to reach peak force (s), time of the kick (s) and peak velocity of the foot (PFV), knee (PKV), hip (PHV) and shoulder (PSV) of the kick ($m \cdot s^{-1}$) were measured. Data were analyzed using the ICC, Wilcoxon paired test or paired sample t-tests, correlation coefficient and Cohen's d. The alpha level of significance was $p<0.05$.

Results: Significant differences were found between the NL and WL conditions in PHV ($p = 0.001$; $d = 0.79$) and PSV ($p<0.001$; $d = 0.60$), impact ($p = 0.045$; $d = 0.49$) and time of the kick ($p = 0.046$, $d = 0.23$, respectively). The NL condition produces higher PHV and PSV and lower impact force and time of the kick.

Conclusions: The 30-kg carried load reduces PHV and PSV and dynamic forces during the front kick. Therefore, individuals who execute a front kick while wearing a load of more than 30 kg should focus on strengthening the muscles associated with maintaining postural stability.

Keywords: dynamic forces • impact • dynamic • kinematics • protection • self-defense • Close combat • personal protective equipment • reaction forces • military backpack

Conflict of interest: Authors have declared that no competing interest exists

Ethical approval: The study was approved by the Ethics Committee of the Faculty of Physical Education and Sport, Charles University in Prague (No. 50/2018)

Provenance & peer review: Not commissioned; externally peer-reviewed

Source of support: Charles University, UNCE / HUM / 032

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Close combat – physical confrontation between two or more opponents at short range involving weapons (knife, stick, firearms and other distance weapons).

Personal protective equipment (PPE) – protective clothing, helmets, thorax-protection system or other equipment designed to reduce the likelihood of serious injury from the impact of small arms fire and fragments.

Military backpack – backpack in which soldiers carry the necessary equipment to survive in the field of combat, usually consisting of a load of 15 kg to 45 kg.

Front kick – kick executed by lifting the knee straight forward while pulling the foot to the hamstring and subsequently straightening the leg in front of the target area.

Dynamic forces – force generated at the start of contact or collision. In close combat, this is the peak force, impact force and impulse of a kick or punch as it hits the body or solid pad.

Peak velocity – specific point in a motion at which the velocity of the measured objects (center of gravity, segment, load, etc.) reaches the highest level.

Load – the amount of something, usually weight, that a body part can deal with at one time [26].

Kinematics – the scientific study of geometrically possible motion of a body or system of bodies motion.

INTRODUCTION

The biomechanical conditions of kicking are key aspects of the net force production and velocity of the kicking movement task, and the front kick is often used as a basic lower limb action in martial arts, self-defense and military training. Performance of the front kick while unequipped is a relatively easy movement task for teaching and strike application in various situations such as close combat. However, military personnel must be physically prepared [1] for close combat while carrying protection, loads and other operational equipment that might influence the front kicking efficiency and tactical possibilities of lower limb strikes.

Previous research has described the influence of personal protective equipment (PPE) worn by military personnel on their performance in repeated running over obstacles or marching [2, 3] during which some subjects wore PPE and backpacks during close combat [4, 5]. Depending on operational need, PPE consists of a helmet and thorax-protection system (i.e., vest with ceramic plates) [6] that weighs approximately 12 kg [7] and a backpack that might weigh up to 45 kg. With this equipment, military personnel should be prepared for sudden close combat moves such as punches or kicks in which wearing ballistic and weighted vests (12 kg), as an example, increases the front kick force impulse and decreases the time to peak force [4, 5]. Thus, PPE might limit certain aspects of kicking performance but also increase other interactional indicators of a kick.

Many previous research studies have investigated the kinetics and kinematics of the front kick, such as velocity [8-11], angular velocity and execution time [12], peak force [4, 5, 8, 13], impact force [4, 13] and impulse [5], without PPE or extra military load. Rapid unloaded digging movements are usually performed in the proximal distal sequence [10, 12, 14]. The first body segment that accelerates is the pelvis followed by the thigh and finally the foot, which achieves the highest velocity [15, 16]. Additionally, the linear velocity of the leg segments is a direct result of interactions among the angular momentum of many joints, more specifically from the leg joints [17]. Thus, the linear velocity is determined as the hip, knee and ankle move toward the target. The peak of the linear velocity reaches the hip and knee at the highest point and ankle immediately before hitting the target [8, 9, 18]. However, the question remains as to how the peak velocity of these segments change when performing a front kick with a military load such as has been reported in pilot studies [4, 19].

The current literature does not address which biomechanical indicators are likely to be changed when a relatively heavy WL is applied and which kicking interactions remain the same. Therefore, the aim of this study was the knowledge about the effects of wearing a ballistic vest and backpack on the peak velocity and dynamic forces during the front kick.

We hypothesized that front kicks performed with WL might result in greater impulse and a quicker time to reach peak force compared with front kicks performed without load (NL) in bare feet conditions.

MATERIAL AND METHODS

Study design

A cross-sectional design was used to compare the effects of a ballistic vest and backpack on front kick dynamics, and the experiments were performed at the Biomechanics Laboratory of Extreme Loading at Charles University in Prague, Faculty of Physical Education, throughout a special military forces self-defense camp (February 2018). Testing occurred in two sessions. Following a familiarization session, the subjects performed two series of six front kicks with maximal effort against a vertically anchored force plate. The subjects performed six barefoot front kicks without load and six front kicks with military loads (boots, ballistic vest, rifle, and backpack; total weight = 30 kg) using their dominant lower limb, which was determined by asking their preference in soccer and combat kicking.

Ethical approval was obtained from the Ethics Committee of the Faculty of Physical Education and Sport (No. 50/2018) together with informed consent, which was signed by all participants in advance. All procedures were performed in accordance with the Declaration of Helsinki 2013.

The subjects performed a general warm-up for a total of 10 minutes, including dynamic movements, stretching and light kicking. Furthermore, subjects completed a pretest of five kicks on the power plate before the experimental measurement. Familiarization was used to establish the individual distance from the force plate needed to execute kicks in the same comfortable position during the testing to ensure the same starting position for each kick in all subjects. The starting position of each front kick established a front stance after the execution of the front kick foot made contact at a mid-range height, typically the abdomen or solar plexus [4]. The front position was adjustable for the optimal distance and referenced a study [20] that found that a long distance resulted in lower impact force than kicks executed from a short distance. The subjects completed one set of six barefoot front kicks and one set of six front kicks while wearing a ballistic vest (a protective CZ 4M modular vest with a ballistic resistance level of IV and 12 kg of weight), military boots and rifle (3 kg), and a backpack (15 kg) with instructions to kick as fast and hard as possible at the force plate. Between each kick, the subject was given 30 s of rest, and a six min rest occurred between kick series [4]. Both sessions of front kick dynamics measurements were completed within approximately 40 minutes.

Participants

Twenty-five healthy male professional soldiers (age: 27.7 ±7.2 yr, body mass: 83.8 ±6.1 kg, body height: 180.5 ±6.5 cm) from the Military Department at the Faculty of Physical Education and Sport at Charles University in Prague volunteered to participate in the study. Due to previous practice in close combat training, which is compulsory in their professional service, the soldiers were able to maintain the proper technique in all front kicks. Soldiers were fit for the term of the experiment and did not undergo any injuries or suffer from any health problems during measurements. The subjects were briefed in advance on the study procedures and were instructed not to perform any physically demanding activities seventy-two hours prior to testing. The additional criteria were front kicking training for at least two years, the absence of any musculoskeletal injury and muscle soreness for two months prior to the study and two years of Special Forces training. The subjects were familiarized with the testing protocols and all aspects of the study before they supplied written informed consent. Additionally, written informed consent was obtained for the publication of images of the subjects pictured in Figure 1.

Dynamics of the front kick

The kinetics data of each front kick were collected at a sampling rate of 2000 Hz from a single triaxial force plate (Kistler 9281; Winterthur, Switzerland), which was synchronized with a 3D motion capture system. For assurance, the height of the impact area of the plate was individualized to each subject's "mid-range" height [4,

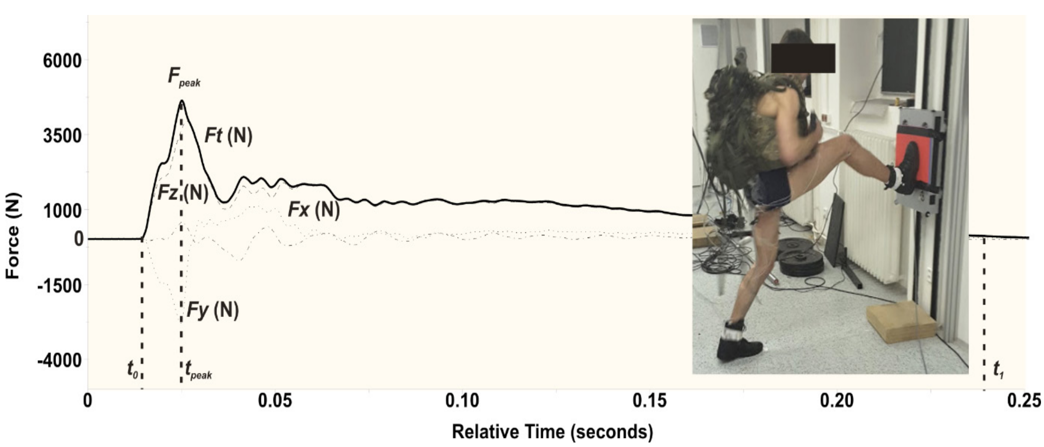


Figure 1. Recorded parameters of a front kick with personal protective equipment. Ft = net force, F_z = force in z-axis, F_y = force in y-axis, F_x = force in x-axis, F_{peak} = peak of net force, N = Newton, t_0 = initial contact time at 30 N threshold, t_{peak} = time to reach peak force, t_1 = termination of contact time at 30 N threshold.

13, 19, 21, 22]. Therefore, the force plate was adjusted along the vertical axis. An illustration of the force-time curve for a single front kick is shown in Figure 1.

The peak impact force (IF_{peak}) was calculated as the maximum value of the 5-ms sliding mean net force exerted in all three directions of x, y, and z [4, 13, 19] (Eq. 1).

$$|\overrightarrow{F_{peak}}| = \max\left(\sqrt{\overrightarrow{F_x^2} + \overrightarrow{F_y^2} + \overrightarrow{F_z^2}}\right) \quad \text{(Eq. 1)}$$

The initial **slope of the force** time curve was calculated as the time to reach the F_{peak} (t_{reach}), defined as the time from a subject's foot contacting the force plate (t_0) at a 30-N net force threshold to reaching the peak force (t_{peak}) (Eq. 2).

$$(t_{reach}) = (t_{peak}) - (t_0) \quad \text{(Eq. 2)}$$

Furthermore, the force impulse was defined by the sampling frequency for each time (Δt). The overall net impulse of a front kick was determined by summing the individual impulses (Eq. 3).

$$I = \int_{t_0}^{t_1} \boldsymbol{F}(t)dt \quad \text{(Eq. 3)}$$

Impact force (F_{impact}) was derived from net impulse and the time to reach peak force (Eq. 4).

$$\overrightarrow{F_{impact}} = \frac{\overrightarrow{I_{peak}}}{t_{reach}} \quad \text{(Eq. 4)}$$

where: I_{peak} was calculated to reach the peak force.

Time of the front kick

The time (s) of the front kick was measured from after the 30 N impact was recorded on the force plate until the foot left the force plate.

Peak velocity of the front kick

The kinematic data of each kick were recorded at a sampling frequency of 500 Hz with a six-camera motion analysis system (Oqus, Qualisys, Sweden) fully synchronized with the force plate and compiled into three-dimensional simulations (Qualisys Track Manager, 2.2 454, Qualisys, Sweden). The force plate was placed in the middle of the calibrated measurement volume lined up with the overall coordinates (mediolateral X, anteroposterior Y and vertical Z). Velocity data were collected from retro-reflective markers attached to the defined anatomical landmark on the subject's malleolus lateralis to express the peak velocity of the ankle and foot (PFV), the distal point of epicondyles lateralis femoris of the dominant/kicking thigh to express the peak velocity of the knee (PKV), the great trochanter of the dominant thigh to express the peak velocity of the hip (PHV), and the acromion of the dominant shoulder to express the peak velocity of the shoulder (PSV).

Statistical analysis

All statistical analyses were performed using NCSS version 2004 (Number Cruncher Statistical Systems, Kaysville, Utah), Matlab (R2019b – academic use) and Excel. Data are presented as the mean and standard deviation of all six kicks, and the data reliability across all six trials was calculated by the intraclass correlation coefficient (ICC). The Shapiro-Wilk test was used to determine whether the data were normally distributed. In the event of a normal distribution, the Pearson's product moment correlation coefficient and coefficient of determination were used to examine the relationships between the weight of subjects and the dynamic forces and between the velocities for PFV, PKV, PHV and PSV of the front kicks. Between-group comparison was performed using the paired sample t-test in the case of a normal distribution or by the Wilcoxon paired test in the case of an absence of normality. The significance level alpha = 0.05 was chosen for all statistical analyses. Cohen's *d* was used to determine the effect size.

RESULTS

The peak velocities among the six front kicks were measured with good to excellent reliability according to the ICC values for both NL and WL, where the ICC values of PFV = 0.56-0.93, PKV = 0.74-0.93, PHV = 0.57-0.94, and PSV = 0.47-0.92. The highest coefficient of determination between weight and impulse of the front kick with *NL* was $R^2 = 0.24$ ($p = 0.014$), and the lowest coefficient of determination between weight and peak force of the front kick with *WL* was $R^2 = 0.12$ ($p = 0.085$). Furthermore, the coefficients of correlation between weight and peak force, impulse, and impact force with NL were r = 0.32 (p = 0.118), 0.44 (p = 0.014), and 0.33 (p = 0.109), respectively, and with WL, the coefficients of correlation were r = 0.35 (p = 0.084), 0.38 (p = 0.06), and 0.35 (p = 0.085), respectively.

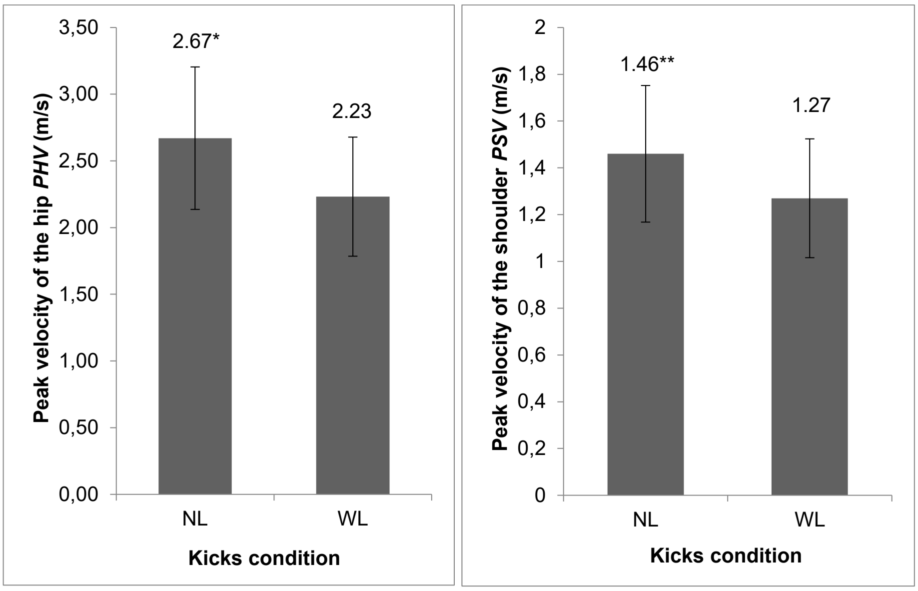


Figure 2. Peak velocity of the hip (PHV) and shoulder (PSV). *Significantly faster than WL ($p<0.05$); **significantly faster than WL ($p<0.01$).

The parametric paired sample t-test revealed differences between NL and WL in PHV (p = 0.0011; *d* = 0.79), and the nonparametric Wilcoxon paired test revealed the difference between NL and WL in PSV (p = 0.0002; *d* = 0.60) (Figure 2).

The PFV was not significantly different in NL (7.72 ±1.12 m/s) and WL (7.71 ±1.05 m/s; p = 0.262; *d* = 0.002) as well as PKV (NL = 5.33 ±0.83 m/s; WL = 5.06 ±0.82 m/s; p = 0.463; *d* = 0.46). Additionally, the most highly correlated values were observed between the velocity of the knee and shoulder with WL and NL and between the foot and knee with NL and between the knee and hip with NL (Table 1).

Table 1. Correlation coefficient between peak velocities of the foot, knee, hip and shoulder

Variables	NL		WL	
	r	p	r	p
PFV x PKV	0.55	0.004	0.18	0.401
PFV x PHV	0.13	0.528	0.36	0.078
PFV x PSV	0.19	0.375	0.19	0.372
PKV x PHV	0.49	0.012	0.09	0.663
PKV x PSV	0.61	0.001	0.57	0.002
PHV x PSV	0.49	0.013	0.46	0.021

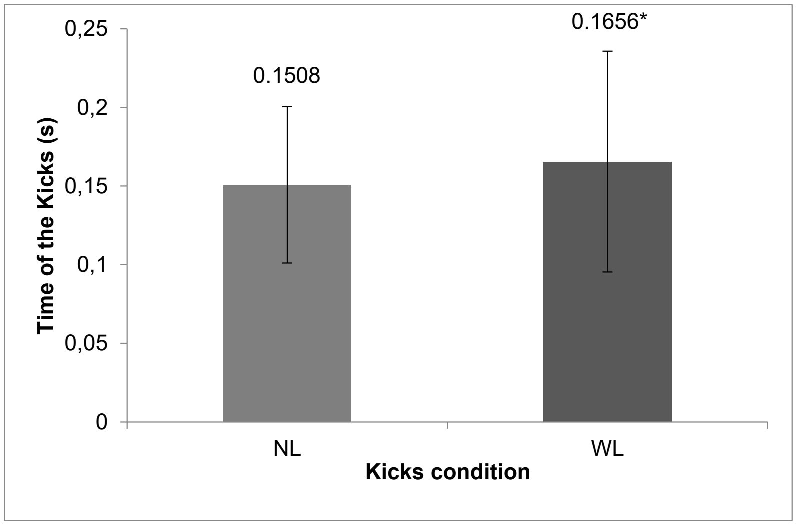
NL – no load; **WL** – with load; **PFV** – peak velocity of the foot; **PKV** – peak velocity of the knee; **PHV** – peak velocity of the hip; **PSV** – peak velocity of the shoulder.

The dynamic forces among the six front kicks were measured with good to excellent reliability (ICC of peak force = 0.76-0.81, time to reach peak force = 0.65-0.80, time of the front kick = 0.35-0.79, impact force = 0.85-0.96, impulse = 0.79-0.90). The time of the front kick was significantly longer with WL than NL (p = 0.0465, *d* = 0.23) (Figure 3), and the impact force was significantly higher with WL than NL (p = 0.0451; *d* = 0.49) (Figure 4).

No significant difference was noted for peak force NL (5604 ±1578 N) compared with WL (5462 ±1515 N; p = 0.381, *d* = 0.09), for the time to reach peak force NL (12.1 ±4.7 ms) compared with WL (10.9 ±2.4 ms); p = 0.224; *d* = -0.29) and for the impulse NL (157.4 ±35.47 N) compared with WL (177.83 ±43.3 N; p = 0.1902; *d* = 0.51).

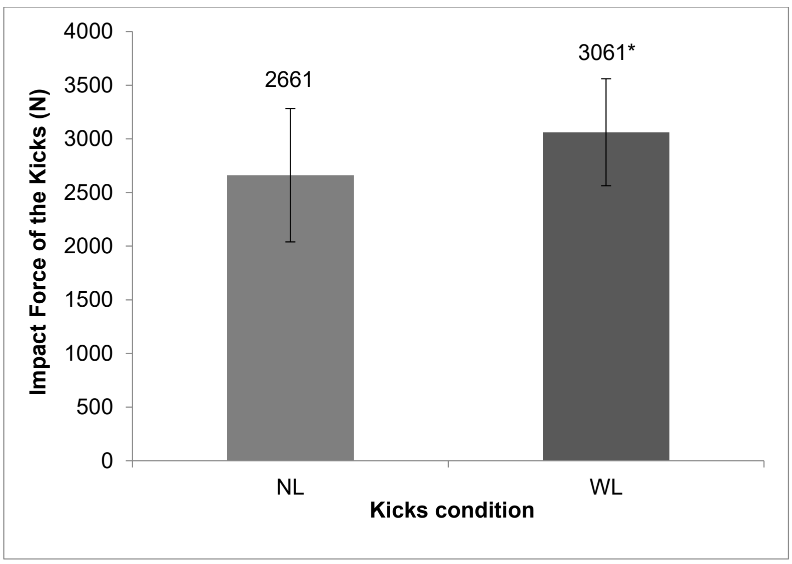
DISCUSSION

Physical fitness is one important demand in the preparation of military personnel and is necessary to prevent physical overburdening and reduce injuries [24], especially when soldiers must adapt to carrying PPE in training and missions. The soldier adopts the split lower limb position in which the lower limb that performs the front kick is placed in the back position during the initial portion of this movement action. The standing lower limb is positioned at the front to maintain movement stability,



*Significantly longer than NL (p<0.05).

Figure 3. Time of front kicks with load (WL) and no load (NL)



*Significantly greater than NL (*p*<0.05).

Figure 4. Impact force of kicks with load (WL) and no load (NL).

which proved to be important when performing a kick with a load. Therefore, our main results are surprising because neither the force impulse nor the time to peak force was different between NL and WL. However, we found that WL increases the time of the front kick and impact force while carrying a 30-kg load.

Peak velocity of the front kick

Kinematic analysis was conducted for kicking from a front stance at the regular distance of one step, such as in previous studies [8, 9 11, 18] in which our subjects achieved an average PFV (7.72 ±1.1 m/s) that was lower than that of other studies (9.9-14.4 m/s [8], 10.3-11.7 m/s [9], 10.4 m/s [11], and 19 m/s [18]). This discrepancy might be explained by the load carried in both tested conditions and the difference in participant level because previous studies used professional and master karate and taekwondo athletes [8, 9, 11, 18]. In general, it is known that a novice can achieve kicking velocities of approximately 6 m/s and might increase this velocity to greater than 10 m/s with sustained practice [8].

However, our participants were not novices, and thus, their lower kicking velocity is probably related to the carried weight, based on the observation that the average PKV of our subjects (5.33 ±0.83 m/s) was similar to that of a previous study (5.95 ±1.24 m/s) [11].

Interesting results were found in comparing the peak velocity of the foot, knee, hip and shoulder and the peak velocity of PHV and PSV, which were slower with WL than with NL, but PFV and PKV were not significantly different with WL compared with NL. This observation might be related to the increased stability requirements, which are maintained by the standing lower limb during the kick.

Furthermore, a similar relationship was observed between PFV and PKV with NL, as in the previous study [11]. Additionally, we found another relationship with NL between PKV and PHV, but both of them were observed only with NL. However, another relationship was found between PKV and PSV and between PHV and PSV with NL and also with WL. This result might suggest that the subjects were forced to transfer the carried load to the kick and thereby move the shoulder of the kicking leg in relation to the velocity of the hip and knee.

Dynamic forces of the front kick

In determining the front kick dynamic forces, it should be considered that energy production might partially depend on the subject's weight [22, 23]. We found that the coefficients of correlation between weight and peak force, impulse, and impact force with NL and WL were in the range of r = 0.32-0.44. However, the coefficients of determination were in the range of R^2 = 0.12-0.24. The low values of the coefficient of determination and a large amount of scattering indicate that the variations with subject weight of the peak force, impulse, and impact force delivered are not linear [22]. Therefore, we did not normalize the dynamic forces to the body mass of the subject in our study.

We note that it is highly difficult to compare our results for NL and WL with those of other studies because no current normative data on the dynamic forces are available. The front kicks were executed against different devices with varying stiffness and damping coefficients of the shock-absorption layer [21, 23]. However, our data are in the range of previously reported impact forces values of 1.17-7.79 kN [22] and professional taekwondo athletes or soldiers reported average impact forces of 3.89 kN [22], 2.9 kN [13], and 3.4 kN [4]. The peak force was 4.5 kN [21] and 5.2 kN [4] without load and 6.3 kN with a load of 15 kg [4]. Comparing our study with another study [4], our subjects achieved greater peak force with NL but lower peak force with WL.

Context between peak velocity and dynamic forces of the front kick

The load (30 kg) that soldiers must carry during the kick was the cause of the change in the body center of gravity and the consequently slower peak velocity of the hip and shoulder. The reduction of the maximum velocity of the hip and shoulder was consistent with a previous study [16] and was probably related to the increasing resistance of the carried load and primarily dependent on the individual's ability to control this load during the front kick. These observations mean that the kick performance with this load depends on the strength of the standing leg and the pelvic muscles that maintain the center of gravity during the front kick. This result supports a previous study in military professionals in which the dynamic forces of the front kick were related to the isokinetic force of the standing leg rotator and the flexors/extensors of the hip [19].

The main limitations of our study include the missing estimation of the current kicking time of training, foot structure [25], and the uncertainty of energy absorption by the soldiers' footwear. However, these are variable factors, which we have to keep to maintain the ecological validity in our testing protocol. Another limitation might be the change in individual kicking technique because subjects probably did not display the same technique in the front kick because of an inability to maintain stability during the front kick with WL. The stability might be improved by strengthening of the pelvic rotators prior to the experiment, but such an intervention was not a component of participant familiarization [19].

CONCLUSIONS

The 30-kg carried load condition does not affect the peak velocity of the foot, the time to reach the peak force of the kick and the peak force. However, the negative effect of the increased load (to WL) slows the execution of the kick by increasing the time of the kick and peak velocity of the hip and shoulder with a simultaneous increase in the impact force of the front kick. So, the hypothesis turned out to be unconfirmed, as the impulse of the force and the time to reach peak force were not different. However, the front kicks with a load of 30-kg had a greater impact force compared to a front kick in bare feet conditions.

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Cite this article as: Vágner M, Maleček J, Hojka V et al. A carried military load increases the impact force and time of a front kick but reduces the peak velocity of the hip and shoulder of the kicking leg. Arch Budo 2020; 16: 69-76