Kinematic determinants of front kick dynamics across different loading conditions

Running head: Kinematic, dynamics loading conditions

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Abstract

Introduction: The efficiency of front kick is related to the kicking technique. Thus, the aim of this study was to find the kinematic determinants of front kick dynamics across different performance and loading levels (no load to 45-kg load).

Materials and Methods: Twenty-four elite and sub-elite professional military personnel (26.8±10.1 years, 84.2±5.4 kg, 181.1±6.4 cm) performed six front kicks into a force plate across five different loading conditions. Three-dimensional kinematics of the kicks was quantified and included velocity of the hip (*V*hip), velocity of the knee (*V*knee), velocity of the shoulder (*V*shoulder), velocity of the foot (*V*foot), angular velocity of the knee (AVknee), and angular velocity of the hip (AVhip).

Results: The main kinematic differences between the two groups were that the sub-elite group had an increased kick time for all loading conditions ($P < .001$) and a lower *V*foot (P=.05) and a decreased *V*hip and *V*shoulder ($P < .05$) in the highest load condition. *V*hip and AVhip were the best predictors (up to $R2$ =0.58; P=.020) of peak force and impact force during no-load or loaded kicking at the elite level. Typical predictors of impulse in the elite group were AVhip, *V*hip, and *V*shoulder and those in the sub-elite group were AVknee and *V*foot.

Conclusions: The kinematic variables provide good predictions of kicking dynamics; however, the best predictor varies with the loading conditions and performance levels. Hip motion is the main differentiating factor.

Introduction

One of the most frequently used techniques in close combat is a front kick, and front kick impact is related to kicking technique. In particular, high impact in the front kick is a function of the quantity of transferred momentum or energy,[2] which is dependent on the level of motor skill and performance.[3] For this reason, many researchers have investigated the dynamics and kinematics of the front kick,[2,4,5,6,7,8,9,10,12,13,15,16,17] where the dynamics typically represents the performance outcome and the kinematics the predisposition for high performance.

In practice, kinematics can be understood as the kicking technique, which varies according to the type of target,[5,14,17] the martial arts technique employed,[14,18] and the performance level.[4,12] Moreover, it has been documented that the maximum front kick velocity is related to maximum knee velocity (r = -0.92), total kick duration (r = -0.73) and total time of foot take off (r = -0.61).[7] Therefore, the hip, knee and ankle kinematics are a useful tool for evaluating performance level, where elite athletes have faster knee angular velocity peaks than less trained athletes.[12] However, there is a lack of information exploring how kinematic differences influence front kick impact.

When performing close combat in real-life environments, military personnel often wear personal protective equipment (PPE) that typically consists of a helmet and thorax-protection system, backpack and other tactical gear depending on the soldier's purpose,[1] which might weigh up to 45kg. Previous research has found that increased carried load can increase the impulse impressed and time of the kick,[8,9,10] however, such an influence of load has not been analyzed for whole lower limb and trunk kinematics.

Since the lower limb and trunk kinematics of the front kick with varying weights corresponding to external military loads is lacking, the aim of this study was to find the kinematic determinants of front kick dynamics at different loading and performance levels. We hypothesized that elite soldiers will maintain the same kinematic pattern with all external loads (no load to 45kg), while sub-elite soldiers would adapt their kinematics to accommodate external loads.

Materials and Methods

This quantitative study was based on a cross sectional design, where participants were highly familiar with the experimental protocol consisting of six kicks at five randomly selected loading conditions. The research was approved by the Ethics Committee of the Faculty of Physical Education and Sport (No. 003/2020. 21 February 2020) and all participants gave informed written consent. All procedures were performed in accordance with the Declaration of Helsinki.

Participants

Twenty four professional soldiers (26.8 ± 10.1 years, 84.2 ± 5.4 kg, 181.1 ± 6.4 cm) with training experience in front kicking were divided into two groups by performance level (elite: 31.8 ± 7.4 years, 86.9 ± 4.4 kg, 179.8 ± 5.4 cm and sub-elite: 22.5 ± 2 years, 81.7 ± 6.1 kg, 182.4 ± 6.3 cm; condition details are in Supplementary Table S1). The participants attended two familiarization sessions to gain experience with the protocol prior to testing and were instructed not to perform any physically demanding activity three days prior to the testing day. All of the soldiers were healthy for the duration of the experiment and did not suffer from any health problems during measurements. Exclusion criteria were traumatic injury affecting performance or musculoskeletal injury within 3 months of the start of the study.

Table S1. Isokinetic net moment during hip external rotation, internal rotation, hip flexion, and extension at different movement speeds.

Peak moment (N·m)	Sub-elite				Elite			
	Mean ± SD	CI lower	CI upper	KS	Mean ± SD	CI lower	CI upper	KS
External Hip Rotation Con 30°·s	**60 ± 16***	50	70	0.11	**78 ± 14***	69	87	0.13
Internal Hip Rotation Con 30°·s	52 ± 13	44	60	0.23	60 ± 8	55	65	0.2
External Hip Rotation Con 90°s	**58 ± 17***	47	68	0.13	**72 ± 14***	63	81	0.17
Internal Hip Rotation Con 90°·s	49 ± 11	43	56	0.15	53 ± 8	47	58	0.19
External Hip Rotation Ecc 30°·s	**71 ± 17***	60	82	0.30	**95 ± 24***	80	110	0.16
Internal Hip Rotation Ecc 30°·s	54 ± 7	49	59	0.13	66 ± 21	52	79	0.31
External Hip Rotation Ecc 90°·s	**67 ± 13***	59	75	0.23	**95 ± 27***	78	113	0.23
Internal Hip Rotation Ecc 90°·s	57 ± 10	50	63	0.21	66 ± 9	60	71	0.11
Hip flexion Con 30°·s	185 ± 26	168	201	0.17	190 ± 37	167	214	0.15
Hip extension Con 30°·s	348 ± 44	320	376	0.16	382 ± 101	317	446	0.15
Hip flexion Con 120°·s	137 ± 21	123	150	0.16	152 ± 32	132	172	0.14
Hip extension Con 120°·s	267 ± 47	237	297	0.17	298 ± 65	256	339	0.22
Hip flexion Con 240°·s	101 ± 18	90	113	0.19	115 ± 27	98	133	0.11
Hip extension Con 240°·s	209 ± 55	174	244	0.18	229 ± 57	193	265	0.15

Con = concentric, ECC = eccentric, SD = standard deviation, KS = Kolmogorov-Smirnov test, CI = confidence interval, * Significant difference between groups by t test $p < 0.05$. The hip rotators are reported in the preferred standing lower limb, Hip flexion and extension is reported in preferred kicking lower limb.

Experimental protocol

Data acquisition was conducted under identical environmental conditions (temperature: 22 ± 1C; relative humidity: 40 ± 5%) and equipment was calibrated before measuring. The familiarization session was used to measure the distance from the force plate for each participant to execute each kick optimally during testing. These individualized distances were then recorded and used to ensure the same starting position for each kick. Each testing session was completed in approximately 40 minutes. Before the experimental measurement the dynamic warm-up lasted 10 minutes and each participant performed a pre-test of five kicks into the force plate. All front kicks began with a front-facing posture and were executed so that the foot made contact at a mid-range height, typical of the abdomen or solar plexus .[2] Each participant was asked to execute his six best kick performance by aiming for the maximum velocity of movement and maximum impact force on the force plate. The order of testing conditions was randomized. The participants executed a single set of six front kicks with bare feet (NL); six front kicks with military boots of 2 kg and a 3 kg rifle (WL1); six front kicks with military boots, rifle and a 10 kg ballistic vest (WL2); six front kicks with military boots, rifle, ballistic vest and a 15 kg backpack (WL3); and six front kicks with military boots, rifle, ballistic vest, and a 30 kg backpack (WL4). Between each kick the participant was given 30 s of rest and between each set of six front kicks 3 min of rest was given.[10] All six recorded front kicks in each set were analyzed.

Kicking performance

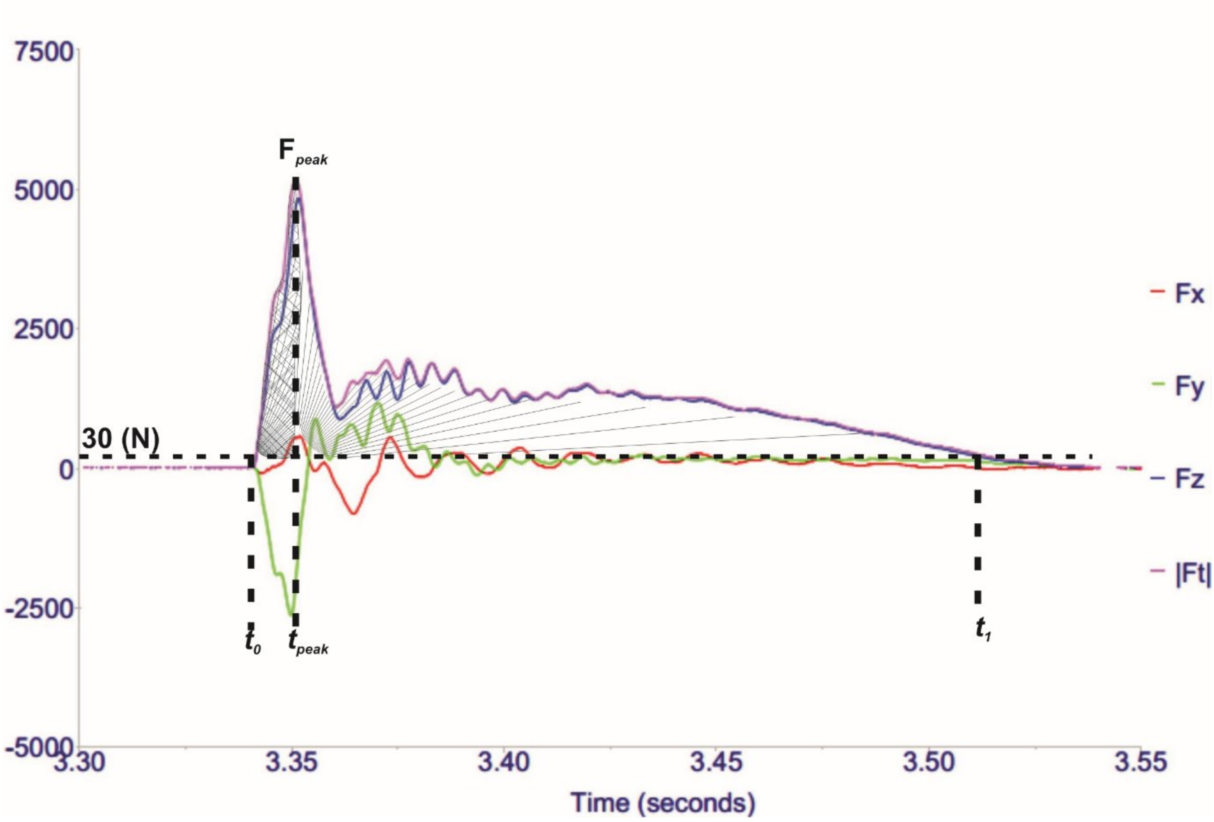
The dynamic data of each front kick were collected at a minimum sampling rate of 1000 Hz from a single triaxial force plate (Kistler 9281; Winterthur. Switzerland), which was synchronized with 3D motion capture system. The force plate had a contact area of 600 mm × 400 mm was covered with industrial strength vinyl (tatami 200 mm), and was mounted in the front as the target with the impact area of the plate individualized to each subject's "mid-range" height.[2,8,9,10]

Peak impact force (F_{peak}) was calculated as the maximum value of the 2ms sliding mean net force exerted in all three directions (x, y, z). Impulse (I_{net}) was calculated according to Eq 1. where F (N) is the net force as function of the kick contact time (t_0 -t_1)

$$\overrightarrow{I_{net}} = \int_{t_0}^{t_1} F(t)dt \qquad \text{(Eq. 1)}$$

and impact force was calculated as I_{net} from initial contact to the time of the F_{peak} divided by the time to reach F_{peak}. An illustration of the force-time curve for a single front kick is shown in Figure 1.

Figure 1. Dynamics variables of the front kick.



t_0 = initial contact time at 30N threshold, t_1 = end of the kick contact time at 30N threshold. t_{peak} = time of reaching the peak force (t_{peak}-t_0). t_1-t_0 = impact time. Lined area is the area of force impulse, cross lined area is the impact force. Ft = net force, Fx,y,z = the force in x,y,z axis.

Kinematics

Three-dimensional kinematic data were collected using a six-camera motion analysis system Qualisys (Qualisys AB, Göteborg, Sweden, Qualisys Track Manager 2.10) sampling at 200 Hz. Data consisted of the position of retro-reflective markers placed on the subject's acromioclavicular joints, anterior superior iliac spine (ASIS), lateral epicondyle, lateral malleoli and on the force plates corners. The force and motion capture data were synchronised by Qualisys Track Manager. The angular displacements of the hip, knee and ankle in the sagittal plane were calculated from the marker positions.

The velocity of each marker was calculated and used to identify the peak velocity of the ankle and foot (V_{ankle}), knee (V_{knee}), hip (V_{hip}) and shoulder ($V_{shoulder}$). The peak velocity of the six front kicks was assessed using ICC. In addition, the angular velocity of the hip (AV_{hip}) and knee (AV_{knee}) joints was computed as the change in angular position and the peaks recorded.

Statistical Analysis

All statistical analyses were performed using IBM SPSS Statistics 25, Matlab (R2019b for academic use) and Microsoft Excel (Microsoft Corporation, Redmond, Washington, USA) using an alpha level of 0.05. Mean intraclass coefficient was used to calculate the reliability of the kicking kinematics and the Shapiro-Wilks test for data normality was calculated separately for both groups. Paired sample t-tests were used to compare the dynamics and the kinematics of the two groups. The group and load comparison was performed using a two way ANOVA with repeated measures (kinematics x load x group) using Tukey's post hoc test for differences between loading conditions. The kinematic variables were tested for dynamic performance prediction using backward regression models for each load separately, followed by between group and load comparison.

Results

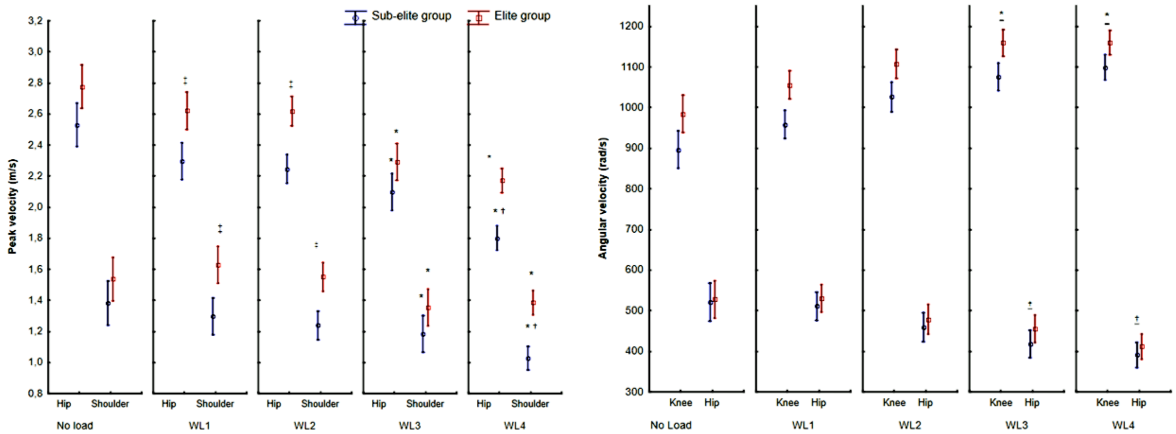
Kicking dynamics were normally distributed and were different between elite and sub-elite groups for time to reach peak force and impact force (Table 1). The kinematic parameters showed good to excellent reliability according to the ICC values (Table 1) and were normally distributed. There was no correlation of F_{peak} with the height or mass of the participants. Between group differences were found in the linear velocities, but not in the angular velocities (Figure 2).

Table 1. Comparison of the kinematics of kicking across groups and conditions

		No load (NL)		Load 5kg (WL1)		Load 15kg (WL2)		Load 30kg (WL3)		Load 45kg (WL4)	
	Group	**Mean ± SD**	**ICC_{CI}**	**Mean ± SD**	**ICC_{CI}**	**Mean ± SD**	**ICC_{CI}**	**Mean ± SD**	**ICC_{CI}**	**Mean ± SD**	**ICC_{CI}**
Peak Force	Sub-elite	5551 ± 1243	0.82-0.98	6078 ± 1147	0.86-0.98	5949 ± 1270	0.86-0.98	5530 ± 1249	0.85-0.98	5382 ± 1000	0.88-0.98
(N)	Elite	5869 ± 1763	0.94-0.99	6305 ± 1723	0.93-0.99	6052 ± 1488	0.94-0.99	5673 ± 1540	0.96-0.99	5306 ± 1361	0.93-0.99
Time to reach	Sub-elite	0.011 ± 0.005	0.85-0.98	0.009 ± 0.002	0.65-0.95	0.00 9± 0.002	0.50-0.93	0.011 ± 0.003	0.64-0.96	0.009 ± 0.002*	0.87-0.98
PF (ms)	Elite	0.012 ± 0.005	0.88-0.98	0.011 ± 0.004	0.81-0.97	0.012 ± 0.005	0.89-0.98	0.011 ± 0.001	0.67-0.96	0.012 ± 0.003*	0.16-0.87
Impact time	Sub-elite	0.166 ± 0.063	0.91-0.99	0.160 ± 0.062	0.97-0.99	0.174 ± 0.074	0.97-0.99	0.186 ± 0.095	0.97-0.99	0.212 ± 0.083	0.97-0.99
(ms)	Elite	0.143 ± 0.033	0.89-0.98	0.134 ± 0.021	0.92-0.99	0.144 ± 0.025	0.01-0.85	0.149 ± 0.030	0.64-0.96	0.173 ± 0.042	0.83-0.98
Impulse	Sub-elite	153.5 ± 29.5	0.87-0.97	168.1 ± 25.8	0.92-0.99	179.8 ± 35.8	0.92-0.99	187.3 ± 42	0.91-0.99	202.1 ± 38	0.90-0.99
(N·s)	Elite	168.7 ± 36.2	0.96-0.99	176.2 ± 33.7	0.96-0.99	183.2 ± 36.4	0.88-0.98	176.2 ± 33.7	0.88-0.98	191.6 ± 46.5	0.95-0.99
Impact Force	Sub-elite	2447 ± 543*	0.77-0.98	3310 ± 546	0.71-0.96	3199 ± 655	0.70-0.96	2921 ± 569	0.62-0.95	2826 ± 494	0.72-0.96
(N)	Elite	3013 ± 824*	0.93-0.99	3737 ± 982	0.94-0.99	3640 ± 929	0.92-0.99	3389 ± 941	0.91-0.99	3142 ± 762	0.9-0.99
Foot velocity	Sub-elite	7.1 ± 0.92*	0.80-0.97	7.3 ± 0.85*	0.78-0.99	7.7 ± 1.06*	0.77-0.99	7.3±1.20*	0.31-0.91	7.2 ± 1.09	0.62-0.94
(m/s)	Elite	8.2 ± 0.92*	0.67-0.96	8.0 ± 0.64*	0.33-0.99	8.4±0.85*	0.89-0.99	8.2±0.73*	0.86-0.98	8.0 ± 0.72	0.40-0.93
V_{knee}	Sub-elite	5.0 ± 0.58	0.77-0.97	4.7 ± 0.36*	0.8-0.98	4.9±0.54*	0.39-0.96	4.9±0.46	0.75-0.97	4.8 ± 0.46*	0.83-0.96
(m/s)	Elite	5.6 ± 0.10	0.81-0.97	5.6 ± 0.91*	0.87-0.99	5.7±0.66*	0.92-0.99	5.3±1.09	0.52-0.94	5.5 ± 0.74*	0.88-0.98
V_{hip}	Sub-elite	2.5 ± 0.38	0.54-0.95	2.3 ± 0.50	0.88-0.99	2.2±0.42	0.68-0.97	2.1±0.49	0.8-0.97	1.8 ± 0.23*	0.68-0.95
(m/s)	Elite	2.8 ± 0.74	0.77-0.97	2.6 ± 0.52	0.7-0.93	2.6±0.34	0.76-0.98	2.3±0.51	0.9-0.99	2.2 ± 0.31*	0.64-0.95
$V_{shoulder}$	Sub-elite	1.4 ± 0.34	0.86-0.98	1.3 ± 0.26*	0.9-0.99	1.2±0.20*	0.9-0.99	1.2±0.28	0.37-0.93	1.0 ± 0.15*	0.82-0.98
(m/s)	Elite	1.5 ± 0.36	0.94-0.99	1.6 ± 0.28*	0.96-0.99	1.6±0.29*	0.94-0.99	1.4±0.30	0.9-0.99	1.4 ± 0.33*	0.93-0.99
AV_{knee}	Sub-elite	896 ±184	0.45-0.99	958 ± 123	0.59-0.98	1026.5±143.8	0.63-0.98	1076±137.4	0.87-0.99	1099 ± 132	0.9-0.99
(rad/s)	Elite	985 ±207	0.3-0.98	1056 ± 149	0.18-0.99	1107.6±157.8	0.27-0.98	1159.2±152.9	0.35-0.95	1160 ±133	0.27-0.99
AV_{hip}	Sub-elite	521 ±121	0.29-0.94	511 ± 105	0.8-0.98	459.2±111.9	0.59-0.97	418.7±84	0.83-0.99	392 ± 61	0.5-0.96
(rad/s)	Elite	528 ± 100	0.46-0.98	531 ± 88	0.23-0.92	479±68.4	0.16-0.95	455.6±69	0.14-0.95	412 ± 82	0.36-0.96
Kick time	Sub-elite	1140 ± 221	0.93-0.99	1282 ± 226	0.83-0.98	1276±211	0.98-0.99	1258±203	0.88-0.98	1269 ± 211	0.97-0.99
(ms)	Elite	1097 ± 132	0.87-0.98	1163 ± 127	0.77-0.97	1163±101	0.78-0.97	1169±154	0.86-0.98	1244 ± 185	0.75-0.97

Values are expressed as mean and standard deviations, **ICC_{CI} = confidence interval for mean interclass correlation coefficient,** * Significant difference between groups, $p < 0.05$. WL1 = 5kg - military boots 2 kg and rifle 3 kg; WL2 = 15kg – military boots 2 kg, rifle 3 kg and ballistic vest 10 kg; WL3 = 30kg - 2 kg military boots, rifle 3 kg, ballistic vest 10 kg and back pack 15kg; WL4 = 45kg - 2 kg military boots, rifle 3 kg, ballistic vest 10 kg and back pack 30kg.

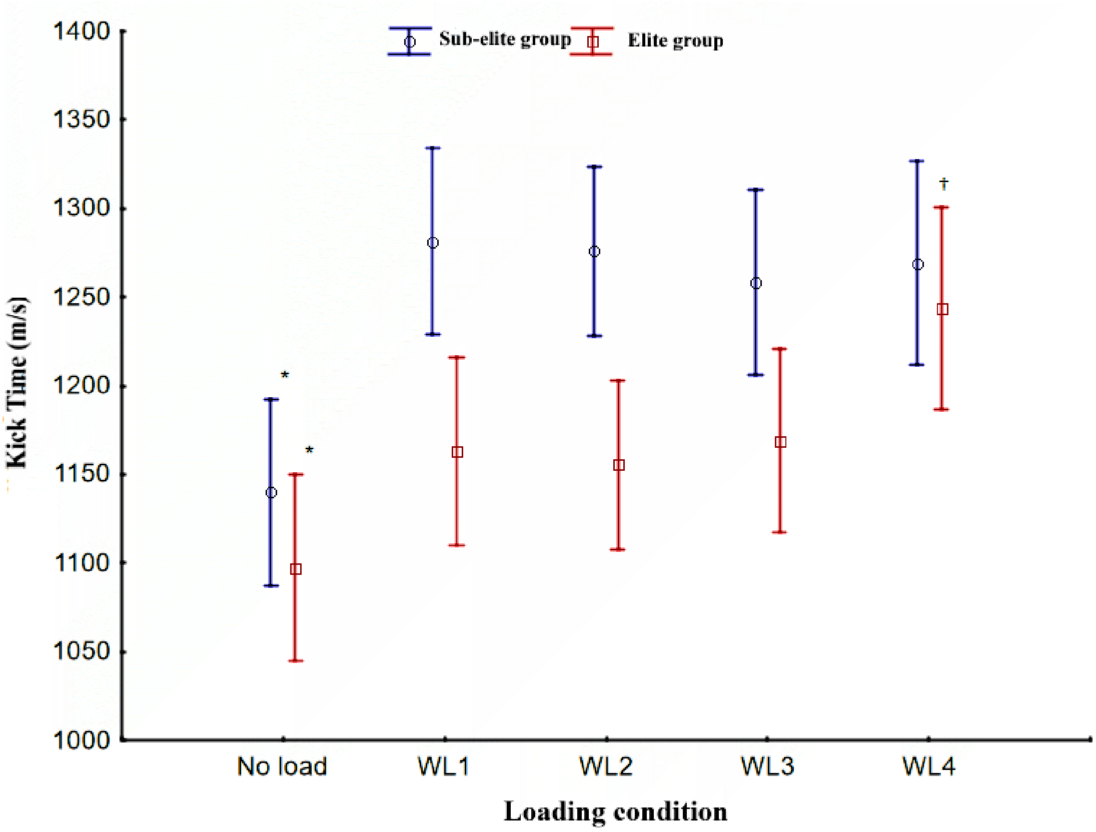
Figure 2. Differences in hip velocity, shoulder velocity, hip angular velocity and knee angular velocity during kicking with different loads



*slower than no-load condition in the same group, ‡ faster than WL3 and WL4 condition, † slower than all other loading conditions in the group. *faster than NL and WL1 condition in both groups, ‡ slower than NL and WL1 condition in both groups, WL1 WL1 = 5kg - military boots 2 kg and rifle 3 kg; WL2 = 15kg – military boots 2 kg, rifle 3 kg and ballistic vest 10 kg; WL3 = 30kg - 2 kg military boots, rifle 3 kg, ballistic vest 10 kg and back pack 15kg; WL4 = 45kg - 2 kg military boots, rifle 3 kg, ballistic vest 10 kg and back pack 30kg.

There were differences between loads in the time of the kick for both research groups ($F_{4, 88}$ =7,52, $p < 0.001$), where post hoc testing showed that the kick without load was faster than the other kicking conditions in both groups and the kick during WL4 was longer than other kicking conditions in the elite group (Supplementary Figure 1).

Figure S1. The total time of the kick in elite and sub-elite soldiers



*shorter all other loading conditions in the group, †longer than all other loading conditions in the group. WL1 = 5kg - military boots 2 kg and rifle 3 kg; WL2 = 15kg – military boots 2 kg, rifle 3 kg and ballistic vest 10 kg; WL3 = 30kg - 2 kg military boots, rifle 3 kg, ballistic vest 10 kg and back pack 15kg; WL4 = 45kg - 2 kg military boots, rifle 3 kg, ballistic vest 10 kg and back pack 30kg.WL4 = 45kg - 2 kg military boots, rifle 3 kg, ballistic vest 10 kg and back pack 30kg.

There were differences between the loads in V_{hip} ($F_{4, 88} = 11$, $p < 0.001$) and $V_{shoulder}$ ($F_{4, 88} = 12$, $p < 0.001$) for both groups, where higher load was associated with decreased movement velocity in WL3 and WL4 when compared to NL. Moreover, the elite group had higher hip and shoulder velocities in WL1 and WL 2 compared to WL3 and WL4, and the sub-elite group had lower hip and shoulder velocities in WL4 than the other conditions (Figure 2).

Further, there were differences between the loads in hip angular velocity ($F_{4, 88} = 23$, $p<0.001$) in both groups, where movement velocity decreased in WL3 and WL4 in comparison to NL and

WL1 (Figure 2). The knee angular velocity differed between loads ($F_{4, 88}$ = 25, p<0.001), where movement velocity increased as load increased from NL and WL1 to WL3 and WL4.

The backward regression provided more prediction models for the elite group than for the sub-elite group (Table 2). For WL4, only impulse could be predicted from the kinematics. V_{hip} and AV_{hip} were the main predictors of peak force and impact force during no-load or load kicking.

Table 2. The best backward prediction models for kinematics and dynamics of kick at different loads and performance level

	Predicant	Sub-elite		Elite	
		Predictors	**Model strength**	**Predictors**	**Model strength**
No load	Peak force	AV_{hip}, V_{hip}	**R^2 = 0.57; p = 0.023**	V_{knee}, AV_{hip}, V_{hip}	**R^2 = 0.65; p = 0.031**
	Impulse	AV_{knee}, V_{foot}	R^2 = 0.43; p = 0.082	$V_{shoulder}$, V_{knee}	**R^2 = 0.49; p = 0.048**
	Impact force	AV_{hip}, V_{foot}	**R^2 = 0.51; p = 0.042**	AV_{hip}, V_{hip}	R^2 = 0.40; p = 0.101
WL1, 3kg	Peak force	AV_{hip}, V_{hip}, V_{foot}	**R^2 = 0.61; p = 0.046**	AV_{hip}, V_{hip}	**R^2 = 0.58; p = 0.020**
	Impulse	AV_{knee}, V_{foot}	**R^2 = 0.78; p = 0.001**	AV_{hip}, $V_{shoulder}$, V_{knee}	**R^2 = 0.59; p = 0.004**
	Impact force	AV_{hip}, V_{knee}, V_{foot}	R^2 = 0.59; p = 0.059	AV_{hip}, AV_{knee}, V_{hip}	**R^2 = 0.65; p = 0.031**
WL2, 15kg	Peak force	V_{hip}	**R^2 = 0.51; p = 0.009**	V_{hip}	**R^2 = 0.54; p = 0.009**
	Impulse	AV_{knee}, $V_{shoulder}$	**R^2 = 0.71; p = 0.004**	AV_{hip}, $V_{shoulder}$, V_{knee}	**R^2 = 0.79; p = 0.005**
	Impact force	AV_{knee}, V_{hip}	R^2 = 0.41; p = 0.096	AV_{hip}, AV_{knee}, V_{foot}	**R^2 = 0.71; p = 0.016**
WL3, 30kg	Peak force	V_{hip}	R^2 = 0.21; p = 0.138	$V_{shoulder}$, V_{knee}	**R^2 = 0.64; p = 0.010**
	Impulse	AV_{knee}, V_{foot}	R^2 = **0.52; p = 0.038**	$V_{shoulder}$, V_{knee}	**R^2 = 0.65; p = 0.008**
	Impact force	AV_{hip}, V_{knee}	R^2 = 0.25; p = 0.274	AV_{knee}, V_{should}, V_{knee}	**R^2 = 0.72; p = 0.013**
WL4, 45kg	Peak force	$V_{shoulder}$, V_{knee}, V_{foot}	R^2 = 0.28; p = 0.431	AV_{knee}, V_{knee} , V_{hip}	R^2 = 0.59; p = 0.055
	Impulse	$V_{shoulder}$	**R^2 = 0.48; p = 0.013**	V_{hip}, V_{foot}	**R^2 = 0.77; p = 0.001**
	Impact force	AV_{knee}, V_{should}, V_{knee}	R^2 = 0.28; p = 0.437	AV_{knee}, $V_{should,}$, V_{knee}	R^2 = 0.34; p = 0.315

AV_{hip} = angular velocity of the hip, V_{hip} = velocity of the hip, AV_{knee} = angular velocity of the knee, V_{knee} = velocity of the knee, V_{foot} = velocity of the foot, $V_{shoulder}$ = velocity of the shoulder, WL 1 = 5kg - military boots 2 kg and rifle 3 kg; WL2 = 15kg – military boots 2 kg, rifle 3 kg and ballistic vest 10 kg; WL3 = 30kg - 2 kg military boots, rifle 3 kg, ballistic vest 10 kg and back pack 15kg; WL4 = 45kg - 2 kg military boots, rifle 3 kg, ballistic vest 10 kg and back pack 30kg.

According to the prediction models for the elite group, AV_{hip} and $V_{shoulder}$ played an important role in achieving higher values of impulse. The sub-elite group was probably no longer able to perform the regular technique of the kick during WL4, as the only predictor of impulse was $V_{shoulder}$. Typical predictors of impulse in the elite group were AV_{hip}, V_{hip} and $V_{shoulder}$ (Table 2) and for sub-elite AV_{knee} and V_{foot}.

Discussion

In this study, the mean maximum velocity of the foot during the execution of the front kick for the NL condition was 7.1 ± 0.92 m/s for the elite group and 8.2 ± 0.92 m/s for the sub-elite group. These values are slightly lower than have been seen in professional karate (elite: 9.5 ± 0.8 m/s; sub-elite: 8.5 ± 0.8 m/s[13]) and taekwondo athletes (11.2 ± 0.34 m/s[17]). When comparing the mean maximum velocity value across conditions there were almost no differences between interventions NL to WL1-4 within the elite or the sub-elite group. On the other hand, there were differences between the elite and sub-elite groups, which we analyzed further.

The presented data demonstrates how differences in technical execution relate to performance level and loading conditions. This includes different expression of reactive forces as has been suggested in a previous study.[4] Based on the presented results, the front kick depends on AV_{hip} and V_{hip} in elite soldiers, which consequently interact with other lower limb movements, where those interactions depend on the carried load.[10] The elite group was characterized by higher V_{foot} in most of the kicking loads, higher V_{hip}, V_{knee} and $V_{shoulder}$ during WL4 load, and an unchanged time of kick during WL1, WL2 and WL3, which shows that performance level highly influences the ability to quickly kick across a range of loading conditions. It has been shown that strike velocity can provide a huge tactical advantage in terms of an opponent's defensive reaction[11] therefore the kicking speed is representative of the practical usefulness of the kicking pattern.[15] As load increased, the elite group showed a more gradual decrease in V_{hip} and AV_{hip} than the sub-elite group, therefore we might conclude that hip movement is the key factor to influence the speed and interactive forces during kicking and should be primarily trained in sub-elite groups. However, the best prediction model varied for each dynamic variable.

The front kick is a common strike used to push away or incapacitate an opponent in close quarters combat or to kick down doors or other barriers. The main operational advantage of the front kick is that it can be performed without load, but also while wearing PPE which is reflective of real combative environments[22]. For operational purposes, operators should be trained to deliver a fast kicking action while maintaining movement control and transferring momentum or energy with the kick[2], which requires strong and fast muscle actions of the lower limb. Therefore, front kick competence not only depends on the kicking technique, but also the strength of specific muscle groups. The experience level groups in this study differed in the concentric and eccentric strength of the external rotators for the preferred stance lower limb (Supplementary Table S1), and not in the strength of hip internal rotators, flexors and extensors. Therefore, we believe that the strength of external rotators is crucial for maintaining the speed and direction of the hip when kicking with load. Based on the characteristics of the elite group (Supplementary Table S1), we would tentatively suggest that operators should be able to produce a concentric hip external rotation moment of about 72 N·m and an eccentric hip external rotation moment of 95 N·m to keep the time of the kick below 1200ms and the peak hip velocity above 2.2 m/s.

Prediction models for achievement of maximum peak force

AV_{hip} and V_{hip} were able to explain up to 60% of peak force variability and the prediction improved by adding V_{knee} in the elite group. Conversely, the sub-elite group increases the force of the front kick by increasing V_{foot}. V_{knee} is related to a better technical execution of the front kick, where the first phase of the kick is characterized by the acceleration of the knee up to the highest position.[7,16] The absence of the V_{knee} relation probably caused the lack of a significant prediction model for WL3 and WL4 in the sub-elite group.

Individuals in the elite group were able to perform the kick correctly up to the addition of a 15kg backpack by increasing shoulder velocity in combination with knee velocity, which together explain up to 64% of the peak force variability. Additionally, even with a 30kg backpack, where it was probably no longer possible to use the shoulder connection, 59% of the peak force variability was achieved by accelerating the hip in combination with the knee velocity and the consequent increase in the angular velocity of the knee. On the other hand, the elite group did not produce higher peak forces than the sub-elite group, which has been observed also for upper limb strikes.[19,20]

Prediction models for achievement of maximum impulse

The efficiency of the strike is not related just to peak force, but also the time over which the force is distributed[21] as both are important determinants of the net impulse (Eq. 1). The best predictors to maximize impulse in the sub-elite group were AV_{knee} and $V_{shoulder}$ which explain up to 71% of impulse variability. However, for WL4 the best predictor was $V_{shoulder}$ only. For WL4, it was evident that the sub-elite individuals were no longer able to maintain the same technique especially in lower limb pattern.

In contrast to the sub-elite group, the elite group's best predictor for impulse was AV_{hip}. However, this only applied to front kicks without a backpack (up to WL2). With a 15kg backpack (WL3), the best predictors for the elite group were $V_{shoulder}$ and V_{knee}, that is, they were probably able to increase the impulse by moving the shoulder and accelerating the knee. However, they were no longer able to perform this technique with a 30kg backpack, where they managed to speed up their hip and foot but not the shoulder.

Prediction models for achievement of maximum impact force

A short and high energy transfer at initial kick contact can increase the kick's efficiency by forcing higher reactive demands for energy absorption by the opponent.[4] In the sub-elite group, only the no-load kick model was significant, and explained 51% of the variability. This means that lower technical level resulted in high variability in kinematics which should couple the velocity and strength of the kick at the same time.

On the other hand, the elite group was able to use AV_{hip} for NL, WL1 and WL2. In combination with AV_{knee} and V_{hip} this explained 65% of the variability for WL1. In WL3, the $V_{hip\ and}$ AV_{hip} was replaced by $V_{shoulder}$, AV_{knee} and V_{knee}, and this model explained 72% of the variability. Elite soldiers probably compensated for the reduced ability to use V_{hip} when kicking with a ballistic vest and backpack. Here again, the added load was manifested by individuals using $V_{shoulder}$ in combination with AV_{knee} and V_{knee}. This technique was effective with a 15kg backpack (WL3), where the model explained 72% variability, but not with a 30kg backpack, where the explained variability dropped to insignificant 34%. It is clear from this that even the elite group was not able to technically accommodate the demands of WL4.

This study has some methodological limitations. In particular, the strength of specific muscle groups is not included in the regression models, and strength has been found as a predictor of the peak net force[10]. The other limitation is the lack of a direct measure of the body forward lean, although participants were instructed to maintain their forward lean. Both of these limitations should be addressed in future studies.

Conclusions

Kinematics can provide predictions of kicking dynamics, however, the kinematic predictors vary with loading condition and performance level. Hip motion is the main differentiating factor. Predictions for the elite group were found for the majority of the variables across conditions, whereas for the sub-elite group prediction models exist only for a limited number of dynamic variables. The performance level is a key factor for predicting and maintaining the kinematic prediction of kicking dynamics with different loads, where only the high load of 45kg resulted in unpredicted peak force and impact force.

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