Segmental kick velocity is correlated with kick specific and nonspecific strength performance in a proximodistal sequence

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B Data Collection
C Statistical Analysis
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Pedro Vieira Sarmet Moreira[1,2ABCD], **Leandro Vinhas de Paula**[3CD], **António Prieto Veloso**[2AD]

[1] Universidade Estadual Paulista "Júlio Mesquita Filho" – UNESP-IB-RC, Rio Claro, Brasil
[2] Faculdade de Motricidade Humana – Universidade de Lisboa, Lisboa, Portugal
[3] Centro Desportivo, Universidade Federal de Ouro Preto – Ouro Preto, Brasil

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Abstract

Background & Study Aim: Explosive strength and vertical jump performance have typically been associated with fast unloaded movements, however their relationship with the martial kick velocity has not been studied. The purpose of this study was to answer the question if kick velocity is correlated with kick specific and nonspecific strength performance, in a *proximodistal* sequence.

Material & Methods: Six male black-belt taekwondo athletes (20.5 ± 4.3 years, 67.1 ± 4.8 kg, 1.78 ± 0.06 m, 21.378 ± 1.9) were evaluated for various strength indicators isometrically, through an adapted *Leg Press* machine, and dynamically, through Counter Movement Jump (CMJ) over a force platform, in ground reaction force (GRF), in linear peak velocities (PV) and time to reach PV (tPV) of lower body segments, during kick, through 3D kinematic analysis at 200 samples/second. Kinematic indicators of kick performance were compared between segments, and then, each kinetic parameter was correlated with them. After, the nonspecific strength parameters were correlated with those specific force parameters that firstly had significant correlation with at least one parameter of velocity. The alpha level of significance was $p < 0.05$.

Results: There were significant differences of timings and velocities between segments. Aditionally, there were significant correlations between specific horizontal GRF and nonspecific strength indicators, especially for CMJ, with the velocities of leg segments during the kick.

Conclusion: The results indicated that, segmental kick velocity is associated with isometric and stretch shortening cycle performance, but modulated by ground reaction force production in a *proximodistal* sequence.

Key Words: ballistic velocity, explosive strength, martial arts, sport performance, vertical jump

Corresponding Author: Pedro Vieira Sarmet Moreira, Rua Dois de dezembro, nº 35, Apto 1002; Flamengo; Rio de Janeiro-RJ 22.220-040, Brazil; e-mail: sarmet_treinamento@hotmail.com

Explosive strength – neuromuscular capability to develop the highest possible strength per unit of time.

Bandal chagui – roundhouse kick technique of taekwondo directed to the chest height.

Proximal – to – distal sequence - temporal order of movement in joints and segments starting from a proximal body segment peak velocity, followed by its relative distal segment aceleration and peak velocity.

Ground reaction forces (GRF) – reaction force acting from the ground to the body, having same magnitude and direction but with opposite sense to the strength the body exerts on the ground.

Counter movement jump (CMJ) – jumping technique performed from the static posture in which the concentric impulse phase is preceded by a quick eccentric phase (counter-movement).

Introduction

In taekwondo, competitors must be able to move with high speed and power [1,2]. Although taekwondo involves punching, most scoring (98%–100%) derives from kicking [1,3]. Taekwondo kicking velocity is extremely important because high speed attacks allow less time for the opponents to react therefore it's more likely to obtain points [3].

In addition, by the current rules, to score a point with a kick, it is necessary to reach a minimal impact force, predetermined for each weight category, measured by the electronic scoring system during the fights. Pieter and Pieter [4] found a significant correlation coefficient between the foot linear velocity and the force of the kick impact (r = 0.72), demonstrating the importance of the velocity to the impact. Although there are many types of kicks in taekwondo, only a handful are frequently used in sparring. The roundhouse kick (*bandal chagui*) is the most popular [5], constituting 50% of all kicks used in a match for male combatants and 89% of all points scored in competition [6].

As the kick is a ballistic movement, it can be influenced by the explosive muscular strength [7-11], because when the time is limited during powerful actions, like taekwondo kicks [5,12], the muscle must exert as much force as possible in a short amount of time. For example, impulse phase of the *bandal chagui* lasts about 350 ms while its aerial phase takes 230–300 ms [5,12,13]. This technique is the fastest kick in taekwondo, because it benefit from *proximodistal* transmission of *momentum* [5], in a way that the first body segment to accelerate is the pelvis [14], followed by the thigh and finishing with the tibia and foot in high velocity [5,15]. But before any significant movement, there is an important impulse of the foot against the ground, in the contrary direction to the proximal segment displacement [13].

The unique research with taekwondo to analyze the ground reaction forces in the *bandal chagui* was the study of Estevan et al. [13] that found significant correlations of these forces with the velocity of thigh and tibia. However, these authors did not analyze the movement of pelvis, which by the view point of the *proximodistal* sequence, is fundamental to starting the movement. Its then believed, that the foot velocity is dependent of the *momentum* transmission from the proximal segments [5], starting by the velocity of pelvis center of gravity, which would be a direct result from the ground reaction forces in the three axis of movement.

These forces gradually begin to then reach an explosive rate of its increase [13]. Explosive strength measures related to fast movements can be obtained through the rate of force development (RFD) calculation [7,8,16,17]. RFD can be defined as the ability to rapidly develop force [17] and it has important functional significance in fast and forceful muscle contraction [7,17]. However, most explosive activities involve muscle contraction in the stretch shortening cycle (SSC) [18], and it is known for the enhancing of performance by the amount of prestretch during the counter movement [19], maximizing the concentric phase of the muscle movement through the storage and use of potential elastic energy from the eccentric phase [20,21], and through the reflex potentiation of muscle activation [20].

The counter movement jump (CMJ) and the kicks, including the round house kick, are tasks that involve the SSC [9,18,21,22], because the knee is flexed soon before extension [2,5,6]. In these movements the knee flexion is a counter movement that serves to stretch the extensor knee muscles before they needs to be shortened, making the muscles able to generate a high final velocity. The crucial contribution of the counter movement seems to allow the muscles to build up a high level of active state and force before start to shortening, so that they turn able to produce more work over the first part of their shortening distance [18].

Markóvic et al. [23] showed that the squat jump (SJ) and even more the CMJ are the most reliable and valid tests for the estimation of explosive power of the lower limbs. Moreover, it has been shown that unlike SJ, CMJ performance has a positive association with the competitive longitudinal ranking of taekwondo athletes [24,25]. As the SJ performance depends mainly on the capacity of neuromuscular recruitment and the contractile muscles properties, while the CMJ also benefits from the elastic force and muscular reflex potentiation [20,21]. Thus, it has been hypothesized that the ability to express the maximal power in SSC movements would be more important for taekwondo performance than concentric (for example, SJ) only movements [26,27].

Bandal chagui has been considered as a *proximodistal* sequencing movement [5,15]. However, the study of Estevan et al. [13] was not able to confirm this affirmation. Because apparently, the time to reach the thigh peak velocity was similar to the timing of peak velocity of tibia and foot. In this study, these data were not statistically compared, therefore, this hypothesis lacks experimental verification. On the other hand, the relationship between specific ground reaction

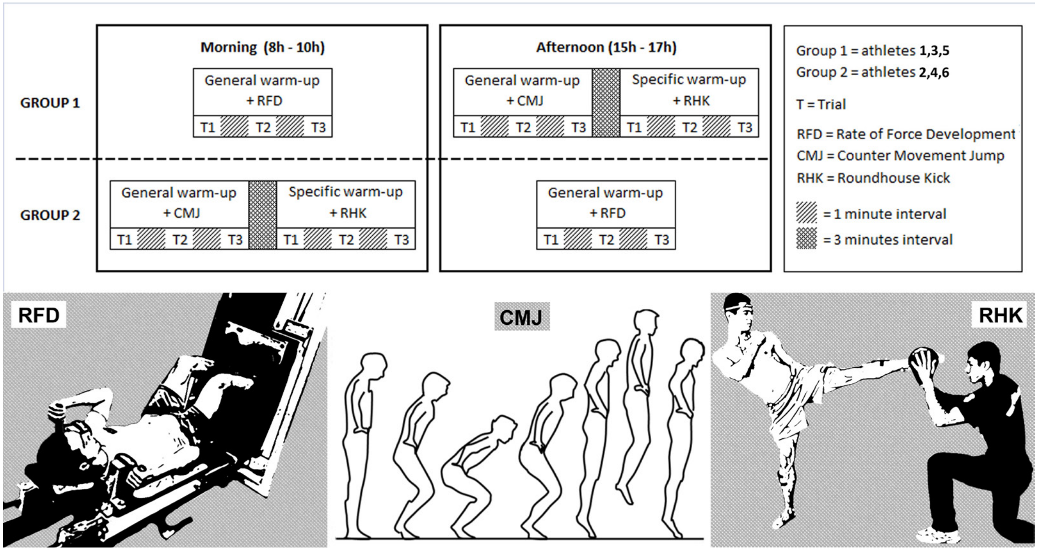

Figure 1. Sequence of tests

rate of force production and taekwondo kick performance, and also, the relationship between nonspecific strength indicators and taekwondo kick performance were never researched.

Therefore, the purpose of this study was to answer the question if segmental kick velocity is correlated with kick specific and nonspecific strength performance in a *proximodistal* sequence. We hypothesized that in *bandal chagui*: (i) Distal segment peak velocity is fastest than peak velocity in each relative proximal segment; (ii) Distal segment peak velocity occurs later than peak velocity in each relative proximal segment; (iii) Distal velocity is correlated with each proximal segment velocity; (iv) Segment velocities are correlated with specific ground reaction forces indicators. Also, as various researches have associated the performance in ballistic movements with non-technical specific explosive power indicators and with contraction in SSC, we further hypothesized that: (v) Segment peak velocity is correlated with non-technical specific rate of force development and counter movement jump performance; (vi) Due to long time to be reached, peak of isometric force has no significant correlation with kick velocity. But if significant, (vii) the relationship between non-technical specific strength indicators and kick velocity are modulated by specific ground reaction force, through significant correlation between specific and nonspecific strength indicators.

Material and methods

Experimental approach to the problem

The methodology of this study was developed to examine if segmental kick velocity is correlated with kick specific and nonspecific strength performance in a *proximodistal* sequence. The measurement of the kinematic variable was made through the *gold-standard* method that is 3D kinemetry. Kick specific ground reaction force and counter movement jump (CMJ) are closed kinetic chain, so we opted to use a closed kinetic chain (leg press machine) exercise to evaluate the isometric strength indicators.

The measurements were done in 2 different laboratories, consequently the tests were randomized over 2 day periods (morning and evening). Athletes were randomly divided in 2 groups that performed the tests in a different order. The RFD, CMJ and roundhouse kick (RHK) were performed with a maximum intensity in order that the intervals between the trials and tests were executed as shown in Figure 1.

During the kick, the foot hits a hand held target paddle (Daedo®, Barcelona, ESP), that is one of the most common targets in TAEKWONDO training, as used in other study [4]. All the participants were familiarized with the evaluations 1 week before. The statistical of the results from counter movement jump and *leg-press* evaluation were realized with the best measured variables of the trials, while in kick results, all indicators used for statistical analysis were selected from the fastest kick (greater foot velocity).

The general warm-ups consisted of 5 minutes running in submaximal velocity followed by five CMJ spaced by 30 seconds each one. The specific warm-up (specific for kick) was composed by, one minute of RHK

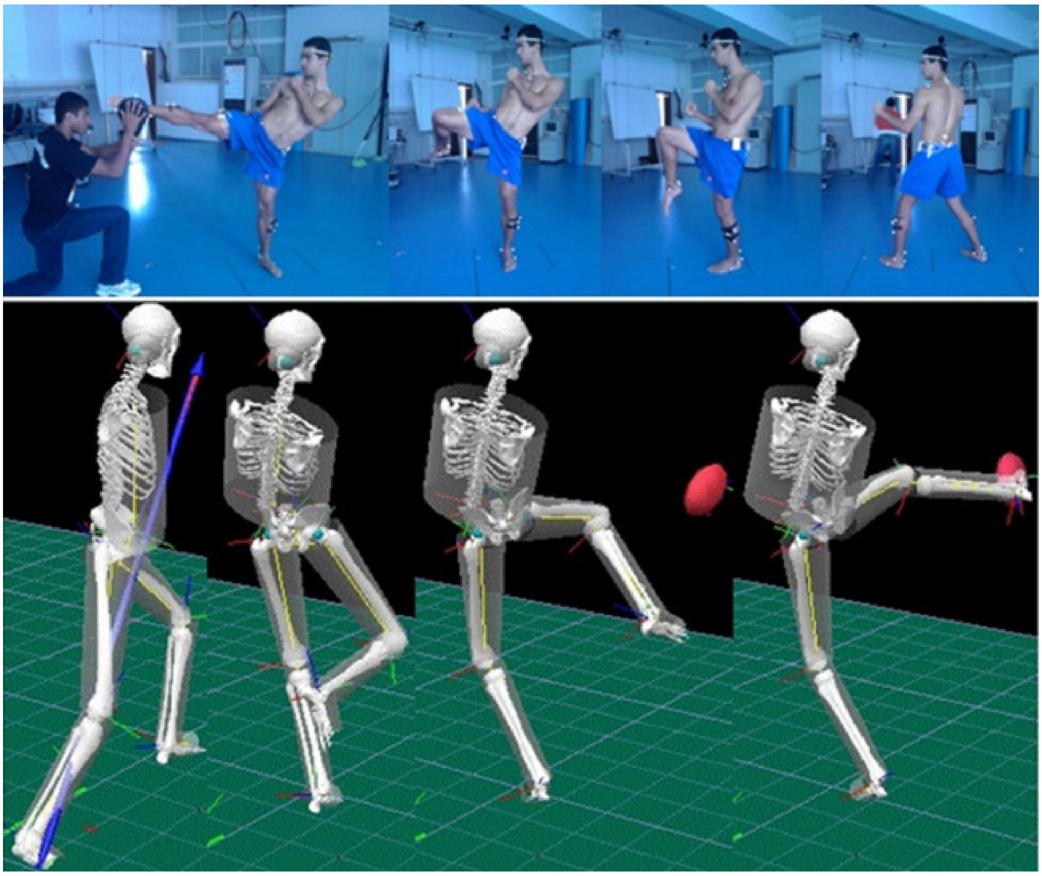

Figure 2. Round house kick technique

with submaximal velocity (alternating legs, totalizing 20 repetitions), two minutes of ballistic stretch exercises (alternating legs at each 2 seconds, totalizing 60 repetitions) described in Little and Willians [28], and by the familiarization (1 minute of 12 rapid RHK's spaced by 5 seconds, with the dominant leg).

Sample

Six male black-belt athletes (age: 20.5 ± 4.3 years, body mass: 67.1 ± 4.8 kg, height: 1.78 ± 0.06 m, BMI: 21.378 ± 1.9) with a minimum of 6 years of training, participated in this study. All of them were playing on the competitive calendar of the Taekwondo Portuguese Federation, in one of the two lighter Olympic weight categories (<68 kg). Subjects were high level athletes that have been participating in the main national tournaments and international competitions classified as Class A by the World Taekwondo Federation (WTF).

Procedures

Before data collection, all athletes completed institutional written informed consents. The institutional review board (Ethical Committee of the University of Lisbon) approved all the study procedures, according to Helsinki declaration. The procedure was constituted by kick technique, motion capture, counter movement jump and isometric strength measurements.

Kick technique

As shown in Figure 2, the RHK starts with a simultaneous knee and hip flexion followed by an external rotation of the thigh of the supporting leg and an internal rotation of the thigh of the kicking leg, introducing hip abduction and finishing with powerful extension of knee joint of the kicking leg. The maximum internal rotation of the thigh of the kicking leg and maximum abduction of the hip, occurred when the foot (*metatarsus*) hits the target [5]. In this study, the horizontal distance between the front of the support foot and the front of the target was adjusted using the value of individual's leg length [28]. The frontal marker of the target was vertically adjusted to the navel height of each athlete in standing posture, with the athlete close to the paddle.

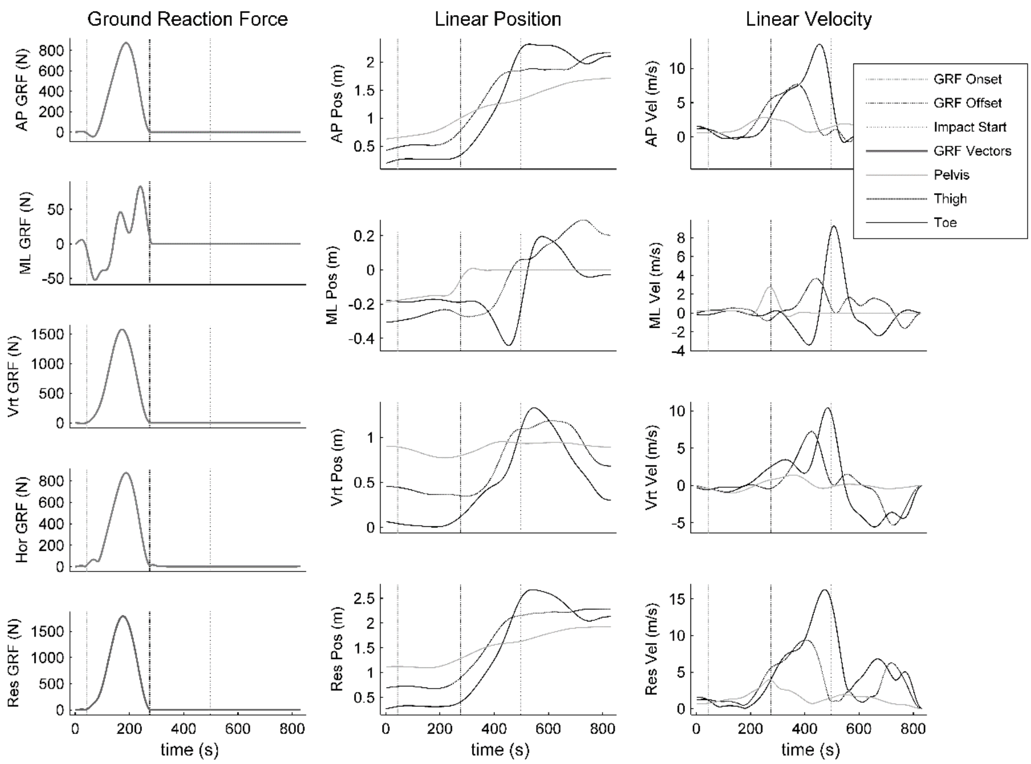

Figure 3. Ground reaction force, linear position and linear velocity of kick executed by one athlete. **AP:** antero-posterior sense; **ML:** medium-lateral sense; **Vrt:** vertical sense; **Hor:** horizontal resultant value (from AP and ML); **Res:** total resultant value (from AP, ML, Vrt); **GRF:** ground reaction force

Motion capture

Motion capture (MOCAP) was collected with 9 cameras Qualisys (model: Oqus-300) operating at 200Hz, with an image resolution of 0.005s, that according to Kim et al. [4] is appropriate to analyze the kick velocity.

Passive-reflective markers were placed on the participants using a modified Helen Hayes marker set [29]. The data collected during the kicks were acquired using the Qualysis Track Manager software (Qualysis Track Manager, Gothenburg, Sweden) and exported to Visual 3D software (V3D) (Visual 3D Basic RT, C-Motion, Inc., Germantown, MD). V3D generates the reconstruction of nine rigid body segments (head, trunk, pelvis, right and left thighs, right and left shanks and right and left feet) (Figure 2). Computed variables were ground reaction force, linear displacement and linear velocity of leg segments and pelvis in the 3 absolute axes. The raw data of force and kinematic output were smoothed through MATLAB 2012 (Mathworks, Natick, USA) routine, with a *Butterworth zero-lag* digital fourth order low-pass filter, with cutoff frequency of 15Hz and 10Hz, respectively (Figure 3).

The impulse phase of kick started when the ground reaction force exceeded the baseline in 1% of body weight, and finished when the ground reaction force turned zero, starting the aerial kick phase, that finished when the foot touched the target (Figure 3), i.e. in the onset of the movement of the paddle center [5]. The kinematic indicators used for analysis were defined as below: (1) PFV, peak of resultant velocity of the distal point of dominant foot; (2) tPFV, time between the foot takeoff and the peak of foot velocity; (3) PTV, peak of resultant velocity of the knee (distal point of dominant thigh); (4) tPTV, time between the foot takeoff and the peak of knee velocity; (5) PPV, peak of resultant velocity of the pelvis center of gravity; and (6) tPPV, time between the foot takeoff and the peak of pelvis velocity. Peak of linear velocities from round house kick has been previously reported with good to excellent reliability (intraclass correlation coefficient – ICC = 0.73–0.97) [13].

Kick ground reaction force *(GRFKick)*

The kinetic indicators used for analysis were peak of force and the rate of force production in different time windows, from the onset of force, calculated through the equation: $RFD_{(\Delta time)} = \Delta force/\Delta time$, were: RFD is the rate of force development; 'Δtime' is the time chosen window (50ms, 100ms or 200ms); 'Δforce' represent the force variation between onset and the final sample from the time window. Also were calculated a continuous plot of RFD with 50ms moving window, to calculate the peak of RFD. All these indicators were calculated in the medium lateral, antero-posterior, vertical axis, horizontal resultant direction and in the total resultant global direction (Figure 3). GRF_{Kick} indicators has been previously reported with very good to excellent reliability (ICC = 0.85–0.97) [13].

Counter movement jump

The counter movement jump (CMJ) was performed as maximal exertion with a Kistler force plate (type: 9865B) at 1000 Hz, and no help of the upper limbs was allowed. The participants were instructed to place their hands on their hips and to keep their body erect throughout the jump. Upon landing, contact was initially made with the toes and the knees fully extended to ensure the body positions at take-off and landing were identical. The participants started from an erect standing posture with knees fully extended (knee = 180°). Upon the verbal command "Go", they made a downward countermovement until the knee reached 90º of flexion and then jumped vertically for maximum height in one continuous movement (Figure 4 "B"). Kinetic data from CMJ has been previously reported with good to excellent reliability (ICC = 0.78–0.98) [30].

To calculate all indicators, we found the start of impulse timing, end of impulse and the land time. Start of impulse was the first sample after the minimal force, which the force signal equaled the body weight. End of impulse was the moment when the force turned zero, and land time was the first sample, after end of impulse, which the force exceeded 1% of body weight for more than 100 consecutive samples. Centre of mass (CM) maximum vertical height achieved during the CMJ was calculated through the flight time that was obtained by the graphic of ground reaction force (GRF). We used the method described by Komi and Bosco [18] to calculate the height of rise of the CM, through the equation 1 where g is the acceleration due to gravity (9.81 m´s^{-2}), t_{air} is the flight time:

$$Heigth\ (m) = \frac{g t_{air}^2}{8} \qquad (1)$$

All kinetic indicators were calculated in the impulse phase: Peak of force and mean force was the maximal and average force, respectively. Peak of velocity and mean velocity were the maximal and average velocity of CM; peak of power and mean power were the maximal and average power impress to the ground, respectively; it was also calculated, the contractile impulse, the time of impulse, the time to reach the peak of force, the time to peak of velocity and the time to peak of power. Impulse was the force integrated in time. Power was calculated multiplying instantaneous ground reaction force by velocity of CM and velocity was calculated by continuous time integration of acceleration curve, which was calculated by equation 2, where: "a_t" is instantaneous acceleration; "GRF_t" is the ground reaction force; "t" is the instantaneous time; "BM" is the body mass in kg.:

$$a_t\ (m{\times}s^{-2}) = \left[\frac{GRF_t}{BM}\right] - g \qquad (2)$$

Isometric strength evaluation

After the warm-up followed by a number of submaximal and maximal preconditioning trials (9), each subject performed three knee extension at maximal voluntary effort (in the *Leg Press Machine* with knee extension at 110º). Subjects were carefully instructed to contract "as fast and forcefully as possible." On-line visual feedback of the instantaneous dynamometer force was provided to the subjects on a computer screen. Trials with an initial countermovement (identified by a visible drop in the force signal) were always disqualified, and a new trial was performed.

Using the same method described in the "kick ground reaction force" section, there was calculated the rate of force production in different time windows (30, 50, 100 and 200 ms), the peak and time to peak of rate of force production and also, the peak of force and time to peak of force. The Leg Press Machine used (Figure 4) is adapted with a dynamometer composed by a square metallic platform which contains 4 load cells (1 in each extremity). The signals of the load cells were analogically added and amplified, and then converted to digital values through an A/D BIOPAC® converter, and this latter was controlled by the Acknowledge® 3.9.1 software. The force sample acquisition rate was 1,000 Hz, and the raw data were digital filtered with a *Butterworth zero-lag* low pass algorithm with cut off set at 10 Hz.

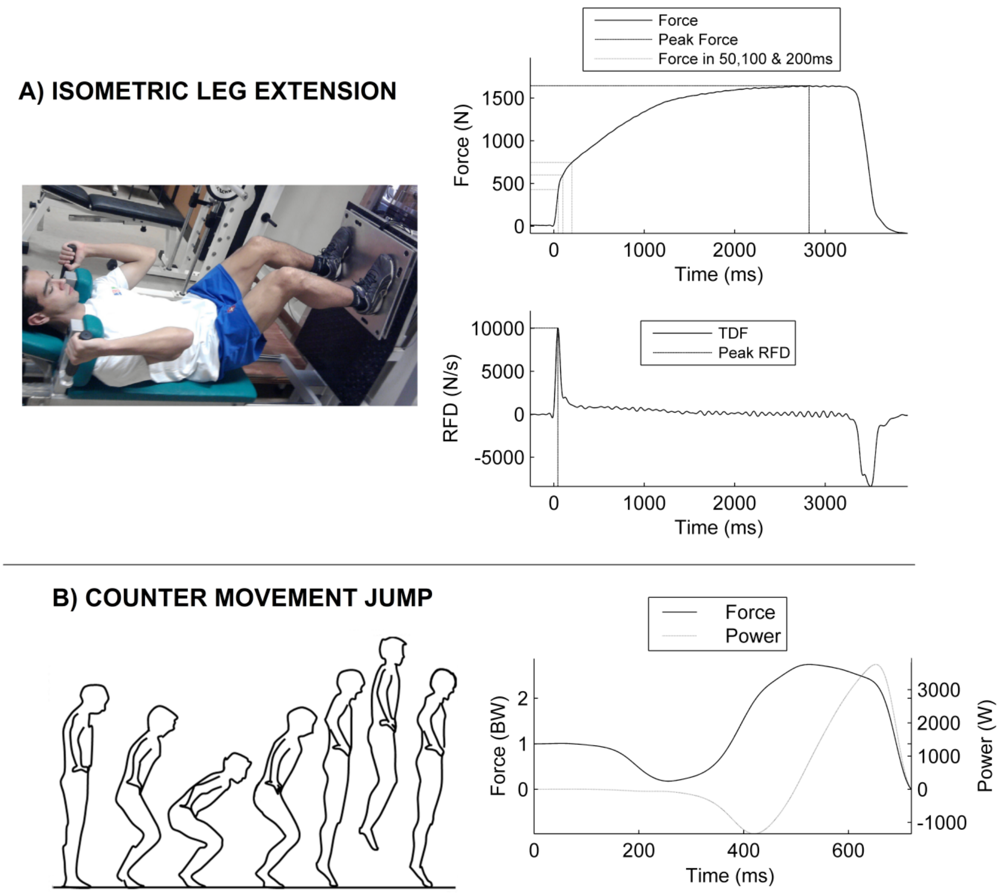

Figure 4. Upper panel (A): isometric evaluation and data processing example. Lower panel (B): counter movement jump evaluation and data processing example

Statistical Analysis

The data was analyzed with SPSS for Windows version 17.0 (SPSS, Inc., Chicago, IL, USA), but the sensitivity power analysis of the sample size and *Cohen's "d" effect size* were calculated using the G*Power 3.1.3 (Dusseldorf, NRW, Germany). Using 6 subjects, this study is 80% powered to detect a correlation coefficient (r) higher than 0.78, to detect an effect size (*d*) higher than 0.81 in *ANOVA*, and to detect an effect size higher than 1.94 in *Tukey* test. Reliability of Isometric Leg Press evaluation was not previously known, then, the intraclass correlation coefficients (ICCs), and 95% confidence intervals (CIs), were determined.

Previously, all data were verified in the presupposes of normality, using the *Shapiro-Wilk* test, and of homocedasticity through *Bartlett* test. To compare the linear peak of velocities (pelvis, thigh and toe) and the time to reach the peak of linear velocity in the body segments, it was used an ANOVA *one-way*. When "*F*" was significant, it was used the *Tukey* test for multiple comparison. Then, when significant differences were obtained from ANOVA or post-hoc comparisons, Cohen's "*d*" score was quantified to analyze the effect size of the comparisons; a *d* value >0.8 indicated a large effect, 0.8–0.5 a moderate effect, 0.5–0.2 a small effect, and <0.2 a trivial effect [13].

After, each kick specific and nonspecific strength parameters were correlated with the linear velocities, through Pearson test, with the data that reached or don't reached the previous assumptions, respectively. After, the nonspecific strength parameters were correlated with those specific force parameters that firstly had significant correlation with at least one parameter of velocity. The level of significance was $p < 0.05$ in all analysis.

Results

The ICC of isometric evaluation for rate of force development in 50ms, 100ms and 200ms were 0.89 (95% CI: 0.55–0.98), 0.91 (95% CI: 0.60–0.99), 0.96 (95% CI: 0.85–0.99), respectively. ICC of isometric

Table 1. Descriptive statistic of kinematic and kinetic indicators

	KICK	M	DP	$CI_{95\%}$		KICK timing	M	DP	$CI_{95\%}$	
				LB	UB				LB	UB
Velocity	PFV(m/s)	16.08	1.74	14.26	17.9	$t_{impulse}$ (ms)	296	78	214	377
	PTV(m/s)	8.96	0.6	8.32	9.59	$t_{aerial\ phase}$ (ms)	222	17	204	239
	PPV(m/s)	2.77	0.59	2.15	3.4	tPPV(ms)	2	18	–17	20
Peak force	ML(N)	285	283	–12	582	tPTV(ms)	116	8	107	125
	AP (N)	645	162	475	815	tPFV(ms)	177	16	160	193
	Vrt (N)	1200	227	961	1438	$tRFD_{MI}$ (ms)	153	71	78	227
	Hor (N)	741	162	571	912	$tRFD_{AP}$ (ms)	151	71	77	224
	Res (N)	1410	235	1164	1656	$tRFD_{Vrt}$ (ms)	206	92	110	302
RFD 50ms	ML (N/s)	573	738	–201	1348	$tRFD_{hor}$ (ms)	160	69	87	232
	AP (N/s)	2255	1514	666	3844	$tRFD_{res}$ (ms)	150	83	63	237
	Vrt (N/s)	4270	3253	856	7684	CMJ	M	DP	$CI_{95\%}$	
	Hor (N/s)	1771	1005	716	2826				LB	UB
	Res (N/s)	4597	3330	1102	8092	Height (cm)	35.2	5.9	28.9	41.4
RFD 100ms	ML (N/s)	993	943	4	1982	$Force_{PK}$ (N)	1820	389	1412	2228
	AP (N/s)	3105	2468	515	5695	$Force_{MN}$ (N)	1156	180	967	1345
	Vrt (N/s)	6124	5008	869	11380	$Power_{PK}$ (w)	3783	726	3021	4545
	hor (N/s)	3132	2085	944	5321	$Power_{MN}$ (w)	2254	519	1710	2799
	Res (N/s)	6880	5364	1250	12509	Vel_{PK}(m/s)	2.72	0.19	2.51	2.92
RFD 200m	ML (N/s)	753	793	–80	1585	Vel_{MN}(m/s)	1.64	0.12	1.51	1.77
	AP (N/s)	1283	714	533	2032	IMP (N*s)	521	71	447	595
	Vrt (N/s)	2102	1241	800	3405	$t_{impulse}$ (ms)	459	109	345	573
	Hor (N/s)	1442	843	558	2327	$t_{peak\ force}$ (s)	318	124	187	448
	Res (N/s)	2540	1464	1004	4076	$t_{peak\ power}$ (s)	395	106	283	506
Peak RFD	ML(N/s)	4406	2390	1897	6914	$t_{peak\ vel}$ (s)	441	104	332	550
	AP (N/s)	7061	2411	4531	9591	LEG PRESS	M	DP	$CI_{95\%}$	
	Vrt (N/s)	13019	4167	8646	17392				LB	UB
	Hor (N/s)	8095	1744	6265	9925	RFD_{50} (N/s)	7227	833	6353	8101
	Res (N/s)	15242	4117	10922	19562	RFD_{100} (N/s)	5258	526	4706	5810
Impulse	MI (N*s)	37	57	–23	97	RFD_{200} (N/s)	3486	412	3054	3918
	AP (N*s)	82	21	59	104	RFD_{PK} (N/s)	8689	988	7652	9726
	Vrt (N*s)	172	40	129	214	$Force_{PK}$ (N)	2027	398	1610	2444
	Hor (N*s)	102	41	60	145	$t_{peak\ RFD}$ (ms)	46	4	42	49
	Res (N*s)	202	54	144	259	$t_{peak\ force}$ (ms)	3190	497	2668	3712

CMJ: counter movement jump performance; **RFD:** rate of force development; **PFV:** peak of foot velocity; **PTV:** peak of thigh velocity; **PPV:** peak of pelvis velocity; **ML, AP, Vrt, Hor:** medial-lateral, antero-posterior, vertical and horizontal sense, respectively; **Res:** resultant; **Vel:** velocity; **PK:** peak; **MN:** mean; **50, 100, 200:** time window; **t:** time

Table 2. Correlations between kinematic and kinetic parameters with performance indicators

Specific indicators		Kick performance			Specific indicators		Kick performance Parameters		
		PFV	PTV	PPV			PFV	PTV	PPV
PFV			0.86*	0.46	Peak RFD	ML	0.51	0.04	–0.52
PTV				0.87*		AP	0.09	0.50	0.41
Peak force	ML	0.31	–0.31	–0.46		Vrt	–0.10	0.19	0.35
	AP	0.38	0.69	0.84*		Hor	0.70	0.75*	0.41
	Vrt	–0.08	0.03	0.49		Res	–0.14	–0.03	0.32
	Hor	0.83*	0.66	0.58	IMPULSE	Ml	0.37	–0.14	–0.20
	Res	0.22	0.24	0.55		AP	0.72	0.73	0.81*
RFD 50ms	ML	–0.07	–0.52	–0.09		Vrt	0.60	0.31	0.41
	AP	–0.50	–0.33	0.09		Hor	0.80*	0.45	0.41
	Vrt	–0.55	–0.37	0.09		Res	0.70	0.37	0.41
	Hor	–0.66	–0.56	–0.32	**General indicators**		**Kick Performance Parameters**		
	Res	–0.58	–0.40	0.09			PFV	PTV	PPV
RFD 100ms	ML	–0.12	–0.53	–0.15	CMJ	Height	0.52	0.77*	0.38
	AP	–0.40	–0.07	–0.06		Force $_{PK}$	0.27	0.60	0.38
	Vrt	–0.52	–0.26	–0.06		Power $_{PK}$	0.64	0.89**	0.90**
	Hor	–0.39	–0.14	–0.12		Vel $_{PK}$	0.60	0.75*	0.46
	Res	–0.51	–0.25	–0.12		IMP	0.73	0.58	0.29
RFD 200m	ML	0.19	–0.14	–0.58	ISOMETRIC	RFD $_{50}$	–0.04	0.22	–0.15
	AP	0.36	0.25	0.38		RFD$_{100}$	–0.11	0.34	0.35
	Vrt	0.31	–0.03	0.38		RFD$_{200}$	0.18	0.62	0.61
	Hor	0.49	0.16	0.20		RFD$_{PK}$	–0.05	0.20	–0.15
	Res	0.37	0.02	0.20		Force $_{PK}$	0.41	0.58	0.81*

CMJ: counter movement jump performance; **ISOMETRIC:** Leg Press Evaluation; **RFD:** rate of force development; **PFV:** peak of foot velocity; **PTV:** peak of thigh velocity; **PPV:** peak of pelvis velocity; **ML, AP, Vrt and Hor:** medial-lateral, antero-posterior, vertical and horizontal sense, respectively; **Res:** resultant; **Vel:** velocity; **PK:** peak; **50,100 and 200:** time window (in ms); * p<0.05; ** p<0.01

peak of rate of force development and peak of force, were 0.86 (95% CI: 0.42–0.98), 0.98 (95% CI: 0.94–1.00), respectively. Finally, ICC of isometric time to peak of rate of force development and time to peak of force were, 0.96 (95% CI: 0.84–0.99) and 0.77 (95% CI: 0.12–0.96), respectively.

Statistical descriptions of our data are shown in Table 1. The comparison between peak velocity of segments through *one-way ANOVA* was significant (p<0.0001; *d*: 0.95); the *Tukey* test revealed difference between PPV and PTV (p<0.0001; *d*: 10.32); PTV and PFV (p<0.0001; *d*: 5.48); and PPV and PFV (p<0.0001; *d*: 10.26). After, the comparison between time to peak velocity of segments through *one-way ANOVA* was significant (p<0.0001; *d*: 0.96); the *Tukey* test revealed difference between tPPV and tPTV (p<0.0001; *d*: 8.27); tPTV and tPFV (p<0.0001; *d*: 4.72); and tPPV and tPFV (p<0.0001; *d*: 10.34).

The correlations between each parameter analyzed with kick velocity of each segments are shown in Table 2. The correlations between each non kick specific indicator analyzed with the indicators that were previously significant correlated with the peak velocity of segments are shown in Table 3.

Table 3. Correlations between nonspecific kinetic indicators with kick specific indicators of ground reaction force

		GRF kick indicators				
		peak of force		peak of RFD	impulse	
		AP	Hor	Hor	AP	Hor
CMJ	Height	0.67	0.57	0.91**	0.28	0.12
	Force $_{PK}$	0.72	–0.13	0.15	0.55	–0.28
	Power $_{PK}$	0.89**	0.40	0.69	0.69	0.09
	Vel $_{PK}$	0.42	0.64	0.91**	0.17	0.29
	IMP	0.02	0.84*	0.78*	0.16	0.72
ISOMETRIC	RFD $_{50}$	–0.16	–0.17	–0.33	–0.24	–0.16
	RFD_{100}	0.40	–0.44	0.05	–0.60	0.40
	RFD_{200}	0.67	–0.07	0.42	–0.31	0.67
	RFD_{PK}	–0.20	–0.20	–0.39	–0.26	–0.20
	Force $_{PK}$	0.84*	0.25	0.90**	0.11	0.84*

CMJ: counter movement jump performance; **ISOMETRIC:** Leg Press Evaluation; **RFD:** rate of force development; **AP, Hor:** antero-posterior and horizontal sense, respectively; **Vel:** velocity; **PK:** peak; **50, 100 and 200:** time window (in ms); * $p<0.05$; ** $p<0.01$

Discussion

To examine the relationship between strength indicators obtained during impulse phase of kick, and also, isolated in isometric or dynamic leg extension evaluation with the roundhouse kick foot velocity, our hypotheses were that segmental kick velocity happens in a *proximodistal* sequence, in a way that kick velocity is correlated with isometric and dynamic force production, but modulated by specific ground reaction force production, through significant correlations between general force output with specific ground reaction force output; and specific ground reaction force performance with kick velocity. About the isometric evaluation, we also hypothesized that only rate of force production, but peak of force was correlated with kick velocity.

We found that kick happened in a *proximodistal* sequence, because the peak velocity of each body segment occurred significant earlier than its respective distal segment. Also, the peak velocities of each distal segment was significantly fastest than its relative proximal segment. Finally, we found significant correlation between pelvis and thigh, and also between thigh and foot velocities (Table 2).

This result is in according with Kim et al. [5] and seems to be obvious but contrast with the results reported by Estevan et al. [13], that stated that round house kick don't used the *proximodistal* sequence. We explain it considering the differences in level of athletes, the absence of pelvis kinematic observation, and absence of statistical foundation by Estevan et al. [13] to this conclusion. Their sample was composed by middle level athletes, while our sample was composed by high level athletes. We believe that more skilled +athletes can beneficiate better from the *proximodistal* transmission of *momentum* then less skilled athletes. In fact, our volunteers were faster than their athletes. In our study, the peak foot velocity was 16.08 ± 1.74 m/s, while in their study, the velocity was 14.3 ± 3.68 m/s. We also consider the pelvis an important segment to this analysis, because this is the first segment to accelerate, while the kicking foot is still giving impulse on the ground.

As we hypothesized, there was significant correlations between ground reaction force production in kick and the velocities of the three analyzed segments (Table 2). However, only those correlations using indicators in horizontal plane, mainly, in the antero-posterior axe, were significant. Because the kinetic of none medio-lateral and vertical indicators had significant correlations with velocities. In addition, only the contractile impulse, the peak of force and the peak of rate of force production significantly correlated with the body segment velocities.

This indicate that those indicators have the ability to influence the final kick performance, but only when they are considered in their maximum capacities, once in kick, each athlete reach its peak of kinetic performance in individualized timings and the calculation of rate of force production through fixe time windows (50 ms, 100 ms and 200 ms) generally are outside of the ideal individual timing. Estevan et al. [13] also found significant correlations of ground reaction force with the body segments peak velocities, but in this research, the velocities were correlated with the peak of force in all axes of movement. One more time, these differences between our researches can be attributed to technical differences between the volunteers.

We also found various indicators nonspecific to kick technique, that significantly correlated with indicators of kick velocity (Table 2). But this phenomenon was predominant when we used the indicators of counter movement jump. In the isometric action, contrary to the hypothesized, only the peak of force significantly correlated with the velocities. It wasn`t expected due to the ballistic nature of the kick. Aagaard et al. [7] has attributed an "important functional significance" to the RFD in fast and forceful muscle contraction, like "sprint running, karate, or boxing".

On the other hand, we can interpret it through temporal analysis of the events. Although the kick is considered an explosive movement, the time of impulse phase is relatively high (>200 ms) while the isometric peak of RFD happened early (<50 ms) (Table 1). In timings lesser than 100ms, the RFD is more related to intrinsic components of muscle fiber (i.e. fiber composition) and at a less extent, with the peak of force [31]. This way, the efficiency of the foot impulse against the ground, which has been shown to be a central aspect to understanding the biomechanics of kick, requires a time of contraction that is more specific to the peak of force than to the contractile characteristics of the muscle fibers [31], and therefore, the impulse indicators would be more correlated with the peak of isometric force and at a less extent, with the isometric RFD.

The CMJ, in turn, responds to this temporal demand, because their impulse phase takes more than 400 ms (Table 1). In the CMJ, was the peak of power, but not the peak of force, the indicator which was better correlated with the velocities. To interpret these results, we need to analyze the data demonstrated on Table 3. We can note that all CMJ indicators, except the peak of force, were correlated with the main kick specific ground reaction force indicators. In the isometric evaluation, in coherent way, only the peak of force significantly correlated with these specific indicators of ground reaction force. These results indicate that the kick ground reaction force production modulate the association between kick velocity and general strength performance.

CMJ is a dynamic strength/power test, while in the present study, the leg press exercise was an isometric evaluation. Four indicators from CMJ and only one from isometric evaluation were significant in the association with kick velocity. The type of muscle contraction can be the key to understand our results, because, Dinn and Behn [32], while comparing 8 weeks of isometric explosive strength training (similar to our isometric evaluation) with the dynamic training (with elastic resistance bands) of boxing punch velocity, found that only the dynamic group decreased the movement punching time. The authors attributed this difference in result to specificity of dynamic versus isometric contraction.

It is long recognized that muscle adapts its contractile properties to exercise training (isometric or dynamic contractions), because Duchateau and Hainaut [33] demonstrated that dynamic training augments to a higher extent maximal muscle velocity of contraction than isometric training (31% vs. 18%) and only dynamic training increases significantly (20%) the maximal rate of tetanic tension relaxation, that is important to the fast relaxation of antagonists during a ballistic movement.

According to these authors, dynamic training essentially increases the velocity of muscle shortening for small loads while isometric training predominantly increases this velocity for high mechanical resistances, which is another indication of the differences in the specificity of different types of exercises on human muscle contraction properties, because ballistic movements are unloaded. They recommend that "training programs should be specifically adapted to the kind of sport and the type of effort performed by the athlete" and our results allow us to recommend that in taekwondo, the strength evaluation should be dynamic to provide information related to the kick specific performance.

Murphy and Wilson [34] also obtained weak correlations (0.08–0.31) between isometric RFD (in bench press) and a dynamic (ballistic) measure of performance (medicine ball throw). Using data of EMG (integral and frequency spectrum) collected during the tasks, they have shown that at least partially, the poor relationship between the isometric tests and the dynamic performance was attributed to different motor units activation patterns between the isometric and dynamic movement.

The actual study is in accordance with Dinn and Behn [32], but another possible argument is the SSC specificity characteristic between the CMJ and the taekwondo kicks. This explanation is derived from the studies of Heller et al [25], Markóvic et al. [23] and Teyl et al. [26], where the first and second authors have shown that explosive leg power, measured by the squat jump (jump without excentric phase), was not a significant predictor of the performance rank in elite taekwondo athletes; and both, the studies of Márkovic et al. [26] and Teyl et al. [27] reported significantly greater results in the CMJ of the principal athletes over the reserve athletes of Croatian and Malaysian national taekwondo teams, respectively. Our different results between the correlations using isometric evaluation and CMJ, confirms the hypothesis of Márkovic et al. [26], which states that the ability to express maximal power in the SSC movements could be one of the most important variables in the taekwondo performance.

SSC exercise training is based on explosive movements such as jumping and bounding to enhance the ability of the muscle to generate power. This kind of training uses the SSC in lower limb muscles, involving a rapid eccentric contraction, immediately followed by a powerful concentric contraction phase. Malissoux et al. [35] associated favorable changes at the single fiber level with significant improvements in various functional variables related to the whole muscle performance (Vertical Jump, Shuttle Run time and Maximal Strength). They concluded that CMJ was the most specific non-invasive test to access changes in SSC performance. They showed that CMJ performance was increased 13% ($P<0.001$) as a result of SSC exercise training. Although SSC training effects are mostly attributed to neuromuscular adaptations (muscle activity patterns of agonists/antagonists and motor unit recruitment strategies) [36,37]. Malisoux et al [35] demonstrates increases in muscle fiber size and enhancements in functional properties of the contractile apparatus.

They showed that 8 weeks of training involving repetitive maximal SSC exercises (plyometric training) increased single-fiber diameter, peak force, and shortening velocity, leading to enhanced fiber power. These beneficial effects were found in type I, IIa, and IIa/IIx fibers. In addition, the normalized peak power, was improved in type IIa fibers and stiffness was increased only in IIa/IIx fibers. The favorable changes noted in almost all the fiber types suggest that SSC exercises represent an interesting training paradigm to improve single fiber force, contraction velocity, and power. Since these changes are greatly associated with the improvement performance in CMJ, our results suggest that they may be important to the taekwondo kick velocity and that plyometric training would be an important method to improve kick performance.

Conclusion

In conclusion, segmental kick velocity is associated with isometric and SSC performance, but modulated by ground reaction force production in a *proximodistal* sequence. Counter movement jump height is more related with taekwondo kick velocity than the isometric strength indicators. This appears to be due to the dynamic specificity between kicks and jumps, because in both the counter movement jump and in the kick, the muscle is stretched before being shortened, and the coordination can influences the performance. Therefore, our results allow us to recommend that in high level taekwondo athletes: i) to obtain high velocity of the foot during the kick, first of all it is important to gain high velocity at pelvis and thigh; ii) impress high level of force in an explosive way to the ground in antero-posterior axe is a key to a fast kick. iii) strength evaluation should be dynamic to provide information related to the kick specific performance. iv) ability to express maximal power in the SSC movements appears to be of major importance to kick velocity. v) CMJ can be an important tool for the talent detection, and to control the training status of an athlete.

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Competing interest

The authors declare that they have no competing interests.

References

1. Kazemi M, Perri G, Soave D. A profile of 2008 Olympic Taekwondo competitors. J Can Chiropr Assoc 2010; 54: 243-249
2. Wąsik J, Shan G. Kinematics of the turning kick – measurements obtained in testing well-trained taekwon-do athletes. Arch Budo 2015; 11: 61-66
3. Jakubiak N, Saunders, DH. The Feasibility and efficacy of elastic resistance training for improving the velocity of the Olympic Taekwondo Turning Kick. J Strength Cond Res 2008; 22: 1194-97
4. Pieter F, Pieter W. Speed and force in selected Taekwondo techniques. Biol Sport 1995; 12: 257-266
5. Kim YK, Kim YH, Im SJ. Inter-joint coordination in producing kicking velocity of Taekwondo kicks. J Sports Sci Med 2011; 10: 31-38
6. Lee JB. A study of kicking techniques of advanced Korea Taekwondo players. 1st ed. Seoul: Coach Field Reports; 1998
7. Aagaard P, Simonsen PE, Andersen JL et al. Increased rate of Force Development and neural drive of human skeletal muscle following resistance training. J Appl Physiol 2002; 93: 1318–26
8. Duchateau J, Semmler JG, Enoka RM. Training adaptations in the behavior of human motor units. J Appl Physiol 2006; 101: 1766-1775
9. Manolopolus E, Papadopoulos C, Kellis E. Effects of combined strength and kick coordination training on soccer kick biomechanics in amateur players. Scand J Med Sci Sports 2006; 16: 102-110
10. Cortis C, Tessitore A, Perroni F et al. Interlimb coordination, strength, and power in soccer players across the lifespan. J Strength Cond Res 2009; 23: 2458-66
11. Chiodo S, Tessitore A, Cortis C et al. Effects of official Taekwondo competitions on all-out performances of elite athletes. J Strength Cond Res 2011; 25: 334-9
12. Falco C, Alvarez O, Castillo I et al. Influence of the distance in a roundhouse kick's execution time and impact force in Taekwondo. J Biomech 2009; 42: 242–248
13. Estevan I, Jandacka D, Falco C. Effect of stance position on kick performance in Taekwondo. J Sports Sci 2013; 31(16): 1815-22
14. Kim JW, Kwon MS, Yenuga SS et al. The effects of target distance on pivot hip, trunk, pelvis, and kicking leg kinematics in Taekwondo roundhouse kicks. Sports Biomech 2010; 9(2): 98–114
15. Sullivan DO, Chung C, Lee K et al. Measurement and comparison of Taekwondo and Yongmudo turning kick impact force for two target heights. J Sports Sci Med 2009; 8: 13-16
16. Ross A, Leveritt, M, Riek, S. Neural influences on sprint running: Training adaptations and acute responses. Sports Med 2001; 31: 409–425
17. Zebis MK, Andersen LL, Ellingsgaard H et al. Rapid hamstring/quadriceps force capacity in male vs. female elite soccer players. J Strength Cond Res 2011; 25(7): 1989-93
18. Komi PV, Bosco C. Utilization of stored elastic energy in leg extensor muscles by men and women. Med Sci Sports Exerc 1978; 10: 261-5
19. Gerodimus BO, Zafeiridis A, Perkos S et al. The contribution of stretch-shortening cycle and arm-swing to vertical jumping performance in children, adolescents and adult basketball players. Pediatr Exerc Sci 2008; 20(4): 379-89
20. Bosco C, Komi PV. Potentiation of the mechanical behaviour of the human skeletal muscle through prestretching. Acta Physiol Scand 1979; 106(4): 467-72
21. Bobbert MF, Gerritsen KGM, Litjens MCA et al. Why is countermovement jump height greater than squat jump height? Med Sci Sports Exerc 1996; 28(11): 1402-1412
22. Kellis E, Katis A. Biomechanical characteristics and determinants of instep soccer kick. Biomechanical characteristics and determinants of instep soccer kick. J Sports Sci Med 2007; 6: 154-165
23. Markóvic G, Dizdar D, Jukic I et al. Reliability and factorial validity of Squat and Countermovement Test. J Strength Cond Res 2004; 18(3): 551-555
24. Heller J, Peric T, Dlouhá R et al. Physiological profiles of male and female taekwon-do (ITF) blackbelts. J Sports Sci 1998; 16: 243-249
25. Moreira PVS, Crozara LF, Goethel MF et al. Talent detection in Taekwondo: which factors associated with the longitudinal competitive success? Arch Budo 2014; 10:295-306
26. Markóvic G, Mišigoj-Duraković M, Trninić S. Fitness profile of elite Croatian taekwondo athletes. Col Antropol 2005; 29 (1): 93-4
27. Teyl, WJ, Kwong, VKW, Rassiah, D, Ooil, CH. Physiological characteristics of Malaysian national elite and subelite taekwondo athletes, Br J Sports Med 2010; 44:1-7
28. Little T, Williams AG. Effects of differential stretching protocols during warm-ups on high speed motor capacities in professional soccer players. J Strength Cond Res 2006; 20(1): 203–207
29. Kadaba MP, Ramakrishnan HK, Wootten ME. Measurement of lower extremity kinematics during level walking. J Orthop Res 1990; 8(3): 383-392
30. Hori N, Newton RU, Kawamori N, et al. Reliability of performance measurements derived from ground reaction force data during countermovement jump and the influence of sampling frequency. J Strength Cond Res 2009; 23(3): 874–882
31. Andersen LL, Andersen JL, Zebis MK et al. Early and late rate of force development: differential adaptive responses to resistance training? Scand J Med Sci Sports 2010; 20(1): 162-169
32. Dinn NA, Behm DG. Comparison of ballistic-movement and ballistic intent training on muscle strength and activation. Int J Sports Physiol Perform 2007; 2: 386-399
33. Duchateau, J, Hainaut, K. Isometric or dynamic training: differential effects on mechanical properties of a human muscle. J Appl Physiol 1984; 56(2): 296–301
34. Murphy AJ, Wilson GJ. Poor correlations between isometric tests and dynamic performance: relationship to muscle activation. Eur J Appl Physiol 1996; 73: 353-357
35. Malissoux, L, Francaux, M, Nielens, H et al. Stretch shortening cycle exercises: an effective training paradigm to enhance power output of human single muscle fibers. J Appl Physiol 2006; 100: 771-779
36. Chimera, NJ, Swanik, KA, Swanik, CB et al. Effects of plyometric training on muscle-activation strategies and performance in female athletes. J Athl Train 2004; 39: 24–31
37. Kyrolainen H, Avela J, McBride JM et al. Effects of power training on muscle structure and neuromuscular performance. Scand J Med Sci Sports 2005; 15: 58–64

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