

Relationships of the expertise level of taekwondo athletes with electromyographic, kinematic and ground reaction force performance indicators during the *dollyo chagui* kick

Authors' Contribution:

- A Study Design
- B Data Collection
- C Statistical Analysis
- D Manuscript Preparation
- E Funds Collection

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Abstract

Background and Study Aim:

Taekwondo is an Olympic combat sport in which the outcome of the match is determined by points scored by kicking. By the competition rules, the roundhouse kick directed to the head (*dollyo chagui*) concedes the tripling of points, compared to that directed to the chest height. The aim of the study is knowledge about kinematic and neuromuscular indicators of the *dollyo chagui* (DC) executed by elite and subelite taekwondo athletes.

Material and Methods:

Seven elite (23.6 ± 2.1 years old; 69 ± 9.5 kg; 168 ± 5 cm) and 7 sub elite (22.4 ± 1.3 years old; 66.8 ± 14.2 kg; 174 ± 11 cm) black belt taekwondo athletes were evaluated on the DC kick performance. Biomechanical measures included angular and linear velocities of leg and pelvis, ground reaction force, premotor time, reaction time, kicking time and cocontraction index (CI) of EMG activation of 8 leg muscles (vastus lateralis, biceps femoris, rectus femoris, tensor fasciae latae, adductor magnum, gluteus maximus, gluteus medium and gastrocnemius lateralis), obtained through the analysis of DC kicks.

Results:

Timing indicator and CI were lower ($p < 0.05$) in an elite group, while linear peak velocities (toe, ankle and knee), angular velocities (knee and hip), and ground reaction force (GRF) were higher ($p < 0.05$) in the elite than in the sub-elite group. The reaction time, co-contraction and speed of kicks are discriminant factors concerning competitive level.

Conclusions:

The specific neuromuscular and technical differences between groups found in this study indicate that to improve the performance of sub-elite athletes these indicators could be useful in monitoring their training status. Furthermore, starting to contract specific muscles early and to perform the kicking phase with the gluteus maximum more relaxed is associated with a more efficient high kick performance. If a coach uses this information to design specific training methods, there could be a potential to improve the kick performance of the athletes.

Keywords:

biomechanics • co-contraction • reaction time • velocity

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Conflict of interest:

Authors have declared that no competing interest exists

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Kick – verb **1.** to strike a ball with the foot **2.** to strike something or somebody with the foot, e.g. in martial arts **3.** to make a thrashing movement with the legs, e.g. when fighting or swimming **4.** (in cricket) to bounce up high and quickly ■ noun **1.** a blow with the foot, e.g. in martial arts **2.** a thrashing movement with the leg when swimming **3.** the striking of a ball with the foot [34].

Dollyo chagui – is classified as a *swing kick*, meaning that the distal segments (foot plus lower leg) benefits of *proximodistal momentum transmission*. That is, the proximal body segment accelerates first than the adjacent distal segments, accumulating and transmitting kinetic energy in the *proximodistal* direction, for achieving a high level of distal linear velocity.

Roundhouse or circular kick – a type of kick defined as throw-like kicks or progressive movements of hip and knee flexion-extension of the kicking leg that start in the sagittal plane and finish in the transverse plane (i.e., swing motion), with the ankle in plantar flexion to hit in lateral body posture with the instep.

Roundhouse kick – a type of kick executed to the chest that generally starts in the sagittal plane and finishes in the lateral plane.

The co-contraction index (CI) – is a suitable way for study the interaction between antagonist and agonist neural drive.

Kinematics – noun the scientific study of motion [34].

Reaction time – noun the interval of time between the application of a stimulus and the first indication of response [34].

Reaction time – is the time from the occurrence of stimulus to the first initiation of movement of the relevant segment of the body [35].

INTRODUCTION

Taekwondo is an Olympic combat sport in which the outcome of a sparring match is determined by points scored by kicking [1]. To score points, these movements need to be fast and with short response time [1, 2-4]. The roundhouse kicks are the most used kind of techniques, resulting in most of the points [3]. By the competition rules, the roundhouse kick directed to the head (*dollyo chagui*) concedes the tripling of points, compared to that directed to the chest height [3].

Dollyo chagui is classified as a swing kick [5], meaning that the distal segments (foot plus lower leg) benefits of *proximodistal momentum transmission* [6]. That is, the proximal body segment accelerates first than the adjacent distal segments, accumulating and transmitting kinetic energy in the *proximodistal* direction, for achieving a high level of distal linear velocity [6, 7, 8]. The linear velocity of leg segments is a direct result of interactions among angular momentum of many joints, more specifically from the leg joints [7, 8]. Then, analysing the leg joints angular velocities should provide important cause-effect information. However, most studies reporting kick angular velocities were performed with karate [9-11]. With taekwondo athletes, Sørensen et al. [7] demonstrated that the angular velocity of the frontal kick is basically determined by three factors: i) motion dependent moment, ii) gravitational moment, and iii) the muscular moment. This last one is a consequence of muscle recruitment, measurable by electromyography [7, 9], where the agonist's muscles generate torque in the intended movement direction while the antagonists generate moments in its opposite direction.

The co-contraction index (CI) is a suitable way for studying the interaction between antagonist and agonist neural drive [9, 11]. Greater co-contraction implies higher antagonist muscle opposition but contributes to the joint stabilisation during impact [12], learning new, fairly complex movements, and fine controlling

the accuracy of a movement [9, 13]. The CI normally diminishes during skill acquisition [13, 14, 15] but in simple movements, it increases proportionally to the angular velocities [9, 16, 17]. However, in combat kick, this response might happen in a different pattern than in simple movements, as it is manifested by the influence of expertise level as well as by the used joint [9, 11, 18]. In a previous study [11] with the roundhouse kick, karateka's had greater gluteus maximum co-contraction during hip flexion phase, but for taekwondo athletes, it is not expected, because they are not supposed to control the impact, breaking the joint movements as they need to in karate. Additionally, controversial results were obtained, depending on the kick phase, the range of motion, analysed muscles and combat sports modality [9, 11, 12, 18].

Another important component of kick response is the reaction time [18]. The reaction time expends from a quarter to two-thirds of the total response time [4, 19, 20]. During a kick, the response time can be divided into three phases: reaction, preparation and kicking phase [18]. Preparation phase is the time when the foot exerts impulse against the ground. In karate, it corresponds to 40-45% of the execution time (preparation plus kicking phase) [10]. To perform this phase efficiently, a high ground reaction force (GRF) needs to be produced, as Estevan et al. [20] shown that GRF is inversely correlated with execution time, and directly correlated with velocities of thigh, shank and foot.

Although the specific skill level can be assessed through various biomechanical indicators, studies with *dollyo chagui* comparing taekwondo athletes of different competitive level have focused only on the effect of impact and temporal aspects of kick [3].

The aim of the study is knowledge about kinematic and neuromuscular indicators of the *dollyo chagui* (DC) executed by elite and sub-elite taekwondo athletes. We hypothesised that elite

athletes would present fast kicks, with higher GRF and lower co-contraction index than sub-elite athletes.

MATERIAL AND METHODS

Participants

The sample was composed of 14 black belt competitors, divided in 7 elite athletes (five male and two female finalists or semifinalists in national competitions, including four national champion and three champions of various international competitions; 23.6 ± 2.1 years old; 69.0 ± 9.5 kg; 168 ± 5 cm with leg length of: 83.2 ± 2 cm; ranging from 1st to 3rd dan; 12.2 ± 8.5 years of training; 15.7 ± 4.7 hours per week of training) and 7 subelite athletes (five male and two female finalists or semifinalists in state competitions without qualify for or achieve podium classification in national competitions: 22.4 ± 1.3 years old; 66.8 ± 14.2 kg; 174 ± 11 cm; with leg length of: 86.1 ± 5.2 cm; 10.4 ± 6.1 years of training; 11.4 ± 5.1 hours per week of training) without significant differences between groups in any anthropometric characteristics, age, grade and time of training. In the sample size calculation previously performed with five elite and five sub-elite athletes, in which an average difference of 141 ms in the total kick time and 2.96 m/s in the foot velocity was found between athlete groups, it was necessary 6 volunteers in each group, so that the unpaired t-student test had 80% of chance of detecting such a difference in the total kick time and the foot linear velocity.

The study was approved by the local Ethics Board (no 8093) and all the subjects were informed about the benefits and risks of the investigation.

All procedures performed in this study were in accordance with the ethical standards of the institutional research committee of the State University of São Paulo and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Design

The study was designed to evaluate choice reaction time, electromyographic, kinematic and ground reaction force (GRF) indicators in taekwondo athletes during 9 executions of *dollyo chagui* intercalated with *bandal chagui* (roundhouse kick to the chest) in a randomized

order and timing between visual stimulus, simulating the average number (18 activities) of high-intensity activities and timing between stimuli (7 ± 2 s) of a taekwondo match [21, 22]. Following, every biomechanical indicator obtained during the kicks were statistically compared between the two groups of athletes. Although *dollyo chagui* and *bandal chagui* kicks were performed in order to mimic a real fight environment, only *dollyo chagui* was considered for analyses. The experimental setup is illustrated in video 1 (<https://doi.org/10.6084/m9.figshare.4828594.v1>).

Procedures

EMG acquisition

Type Ag/AgCl bipolar electrode (Miotec® Double, 20 mm distance between electrodes) were attached to the skin, on the belly of the following muscles: gastrocnemius lateralis (GL), vastus lateralis (VL), rectus femoris (RF), biceps femoris (BF), adductor magnum (AM), tensor fasciae lata (TFL), gluteus maximus (GM), and gluteus medium (Gmed). The electrodes' positioning was carefully set according to Hermens et al. [23]. Wireless transmission Telemetry DTS (Noraxon®), with an acquisition frequency of 3000 Hz and an analogy filter operating in a frequency band from 20 to 500 Hz was used.

Kinetic and kinematic acquisition

Athletes had 39 markers placed according to Plugin Gait marker set. Next, they warmed up for 15 minutes [18], followed by 5 minutes rest. The main evaluation was composed by 18 roundhouse kicks (9 *bandal chagui* and 9 *dollyo chagui*) with the dominant leg positioned distally to the target and supported on a force platform OR-6 (AMTI®) spaced in a horizontal distance from the dummy (BoomBoxe®) equivalent to the lower limb length [6]. One LED in the dummy's head and another in the thorax were microcontrolled by MATLAB (Mathworks® 2012, Inc.) routine. During two minutes, the order and time between stimuli were randomised in a Gaussian mode, with a mean of 7 ± 2 s time interval [22, 18]. Athletes were oriented to kick the fastest and most forceful as possible each time the LEDs turned on. NEXUS motion capture system (Vicon®, v.2.0) recorded the kicks through 7 cameras at 250 frames per second.

Measures

Kinetic and kinematic processing

Kinetic and kinematic data were processed

Velocity – *noun* the rate of change of position in a given direction, composed of both speed and direction [34].

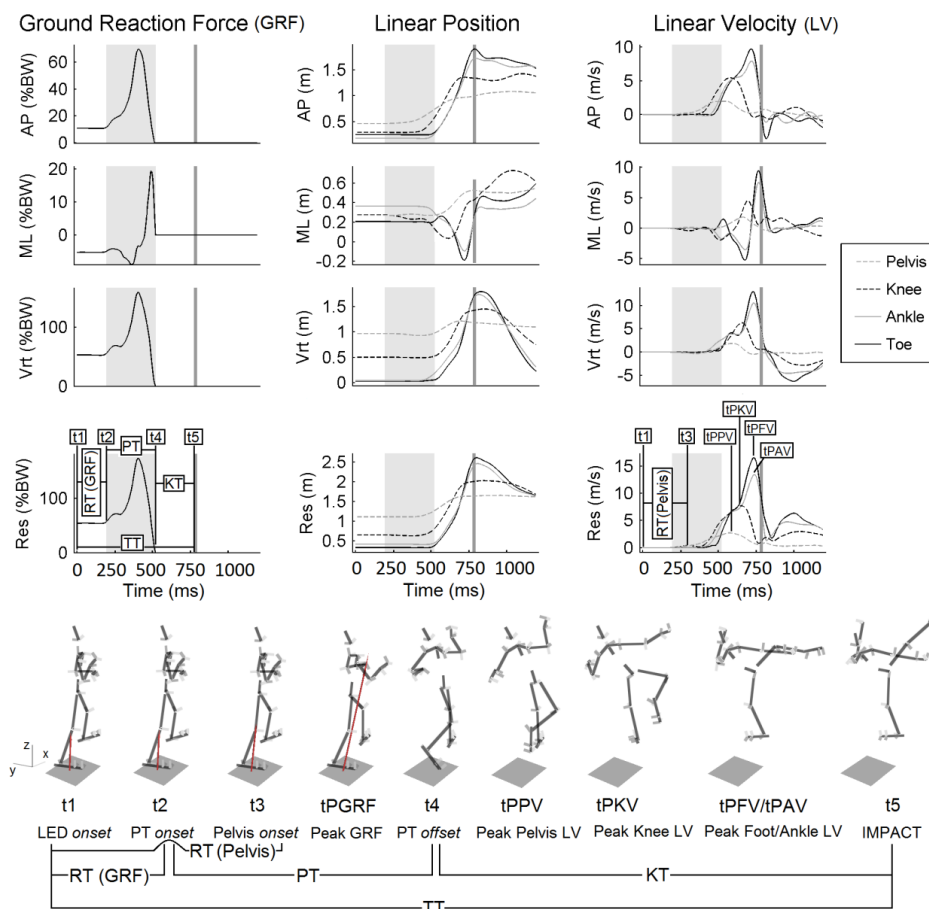


Figure 1. Example of ground reaction force and linear kinematic data processed from an elite athlete: **AP, ML and Long** anteroposterior, mediolateral and longitudinal direction, respectively; **Res** resultant data of tridimensional vector summation; **%BW** percentage of body weight. Areas of light grey and dark grey cover the preparation phase and impact phase of kick, respectively. **t** time markers; **LED** LED onset; **RT (GRF)** kinetic reaction time; **RT (Pelvis)** kinematic reaction time; **PT** preparation time; **KT** kicking time; **TT** total time; **IMPACT** target impact onset.

using NEXUS software (video 2; <https://doi.org/10.6084/m9.figshare.4828597.v1>), generating data of ground reaction force (GRF), linear (Figure 1) and angular kinematic (Figure 2). Data from force platform and kinematic data were smoothed with Butterworth zero-lag Low-Pass filter at 85Hz and 10Hz (cut off frequencies determined through residual analyses), respectively. The onset of visual stimuli (t_1) was the moment when each LED turned on, polarised with >2 V of electric tension. The onset of kinetic reaction (t_2) for the kick preparation phase was when the resultant GRF systematically started to rise above the baseline in 2.5% [18] of the difference between the peak GRF and the baseline value. The onset of kinematic reaction (t_3) was when the Pelvis (anterior superior iliac spine marker of dominant leg side) started to move toward the target in at least 1 cm from the initial

position. Both, the offset of preparation phase and the onset of kicking phase were determined when the resultant GRF turned zero (t_4) [6]. The end of the kicking phase (t_5) was when the foot touched the target. These events were identified through MATLAB routine. Following, the kinetic ($t_2 - t_1$) and kinematic reaction time ($t_3 - t_1$), the preparation phase ($t_4 - t_2$), the kicking phase ($t_5 - t_4$) and the total kick phase ($t_5 - t_1$) were determined (figure 1). The rate of force development (RFD) and the peak of anteroposterior, mediolateral, vertical, and resultant forces were determined during the preparation phase. RFD was calculated as follows:

$$RFD (BW\% \cdot s_{-1}) = \Delta Force (BW\%) / \Delta time (s) \quad (1)$$

for $\Delta time$ being the elapsed time from the instant when the resultant GRF reached 20% of the difference between peak force and

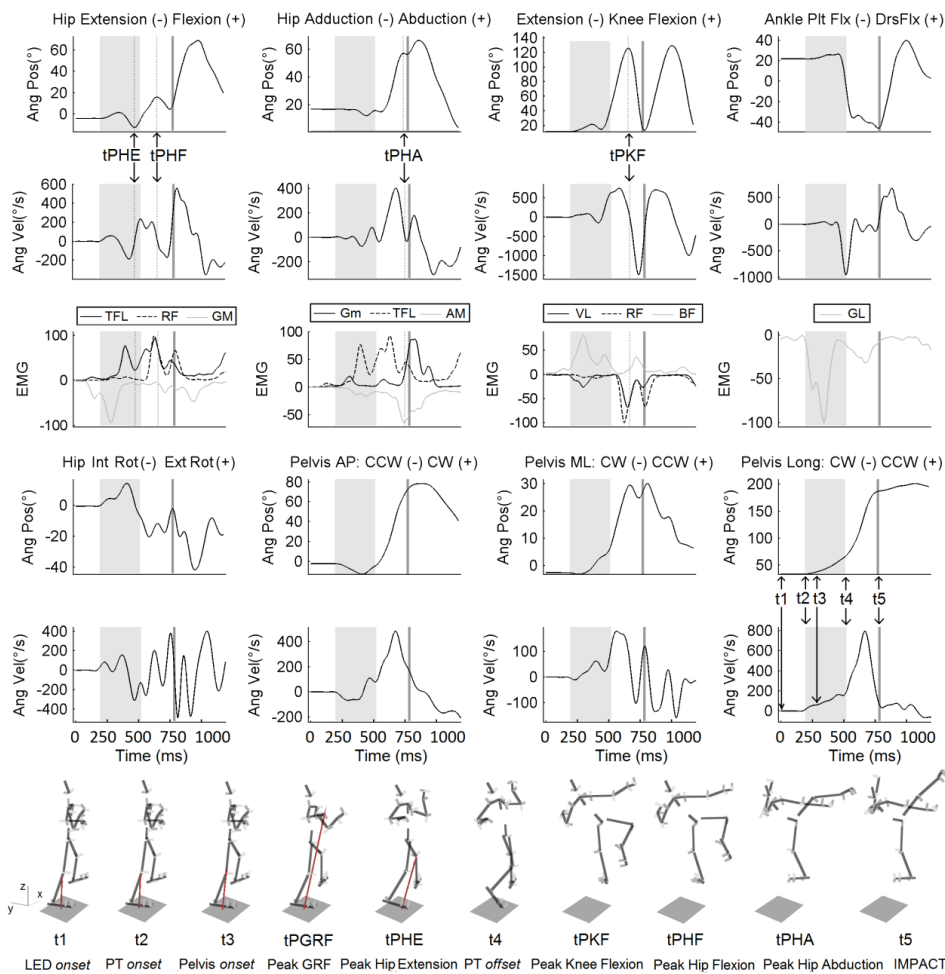


Figure 2. Example of angular kinematics and EMG data processed in an elite athlete (in order to facilitate visualization, EMG linear envelope of antagonist muscles are plotted in the opposite direction in the ordinate axis): **Plt Flx** plantar flexion; **DrsFlx** dorsiflexion; **Ang Pos** angular position; **Ang Vel** angular velocity; **EMG** electromyographic signal (areas in light gray and dark gray cover the preparation phase and impact phase of kick, respectively). Vertical dotted lines mark the peaks of angular position. **GL** gastrocnemius lateralis; **VL** vastus lateralis; **RF** rectus femoris; **BF** biceps femoris; **AM** adductor magnum; **TFL** tensor fasciae lata; **GM** gluteus maximus; **Gmed** gluteus medium. EMG lines are plotted negative to show opposite force generation related to the other plotted EMG profiles (for example, GL is negative because its muscle function is the plantar flexion, with negative sense). **Rot** rotation; **Ext** external; **Int** internal; **AP, ML and Long** rotation in the anteroposterior, mediolateral and longitudinal axis, respectively; **CW** clockwise sense; **CCW** counter-clockwise sense; **t** time markers; **GRF** ground reaction force.

baseline until it reached 80% of that value. The linear and angular velocities of the leg segments were calculated through the discrete derivative. Estevan et al. [20] showed that the reliability of kinetic and kinematic indicators of the roundhouse kick in taekwondo athletes was good to excellent (ICC = 0.73-0.97).

EMG processing

Data from EMG were rectified, smoothed using a Butterworth zero-lag low-pass filter at 10Hz and normalised by the peak dynamic method [24], in order to obtain the linear envelope signal (LE)

(Figure 2). The cocontraction (CC) between hip extensor (GM) and flexor (TFL or TFL + RF), during hip flexion; between knee flexor (BF) and extensors (VL or VL + RF) during both knee flexion and extension; and between hip adductor (AM) and abductor (Gmed) during hip abduction were calculated as follows:

$$CC (\%) = 100 \cdot \frac{\text{Antagonist}_{LE}}{(\text{Agonist}_{LE} + \text{Antagonist}_{LE})} \quad (2)$$

were “Antagonist_{LE}” and “Agonist_{LE}” is the agonist and antagonist LE area, respectively. Finally, to calculate the “premotor time” (PMT), the time

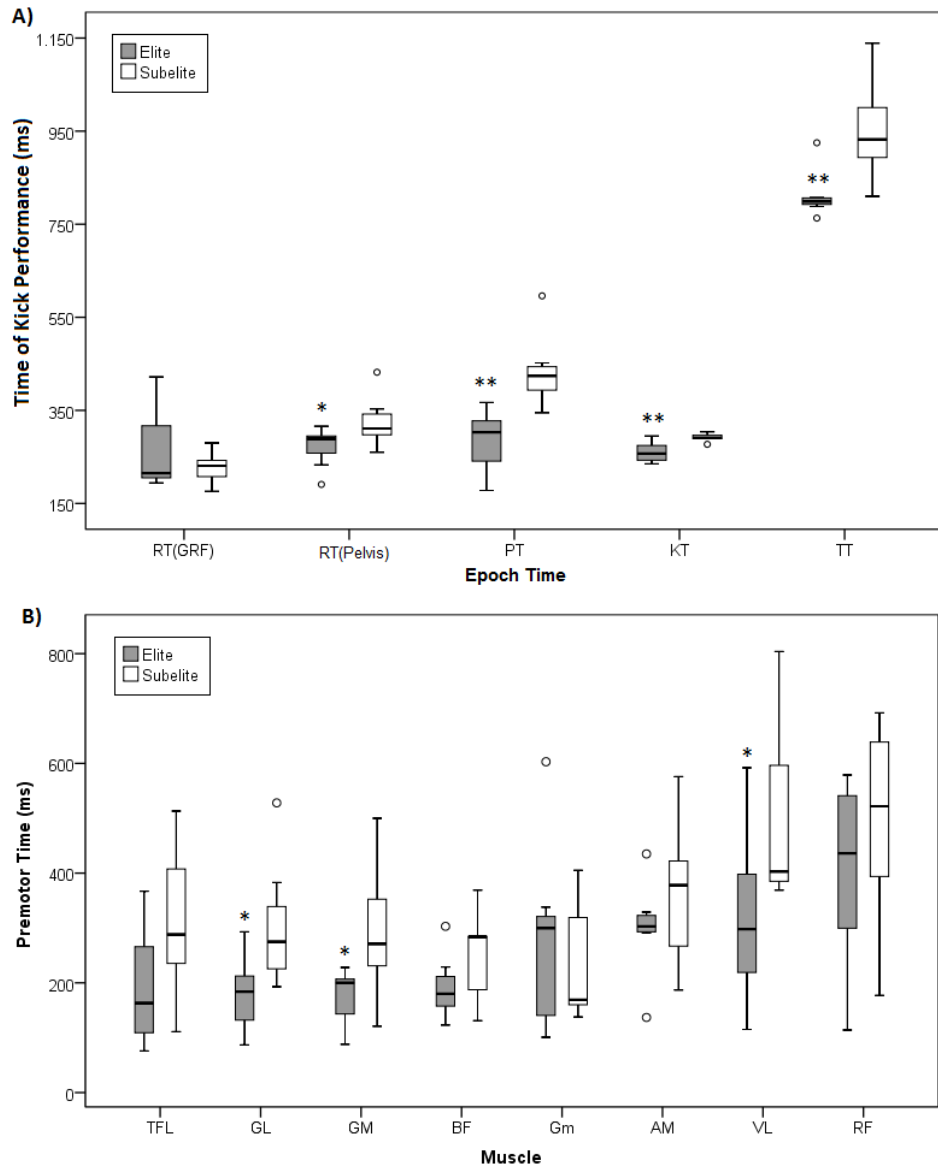


Figure 3. Comparative plots of time of kick performance (A) and premotor time (B), between elite and sub-elite athletes. Boxplot represent Median, 1th, 3th quartile and error bars represent data limits: **RT(GRF)** reaction time using kinetic onset; **RT(Pelvis)** reaction time using kinematic onset; **PT** preparation time; **KT** kicking time; **TT** total time; **GL** gastrocnemius lateralis; **VL** vastus lateralis; **RF** rectus femoris; **BF** biceps femoris; **AM** adductor magnum; **TFL** tensor fasciae lata; **GM** gluteus maximus; **Gmed** gluteus medium; *p<0.05; **p<0.01; ° statistical outliers for specific variables.

between visual stimulus and onset of LE were determined. EMG onset was obtained through two consecutive steps:

1) Determination of “onset 1” as the first sample (“n”) which

$$\left(\sum_n^{n+50ms} LE\right)/50ms > 10\% \cdot (\text{Peak}_{LE} - \text{Baseline}_{LE}) \quad (3)$$

where “Peak_{LE}” is the Peak of the LE signal, and Baseline_{LE} is

$$\left(\sum_{t_1}^{t_1+50ms} LE\right)/50ms \quad (4)$$

for “t₁” is the instant of the LED onset;

2) Starting from the “onset 1”, the “final onset” was the first sample “n” where

$$LE(n) > 1\% \cdot (\text{Peak}_{LE} - \text{Baseline}_{LE}) \quad (5)$$

The percentage threshold values and the time window used to determine the EMG onset were

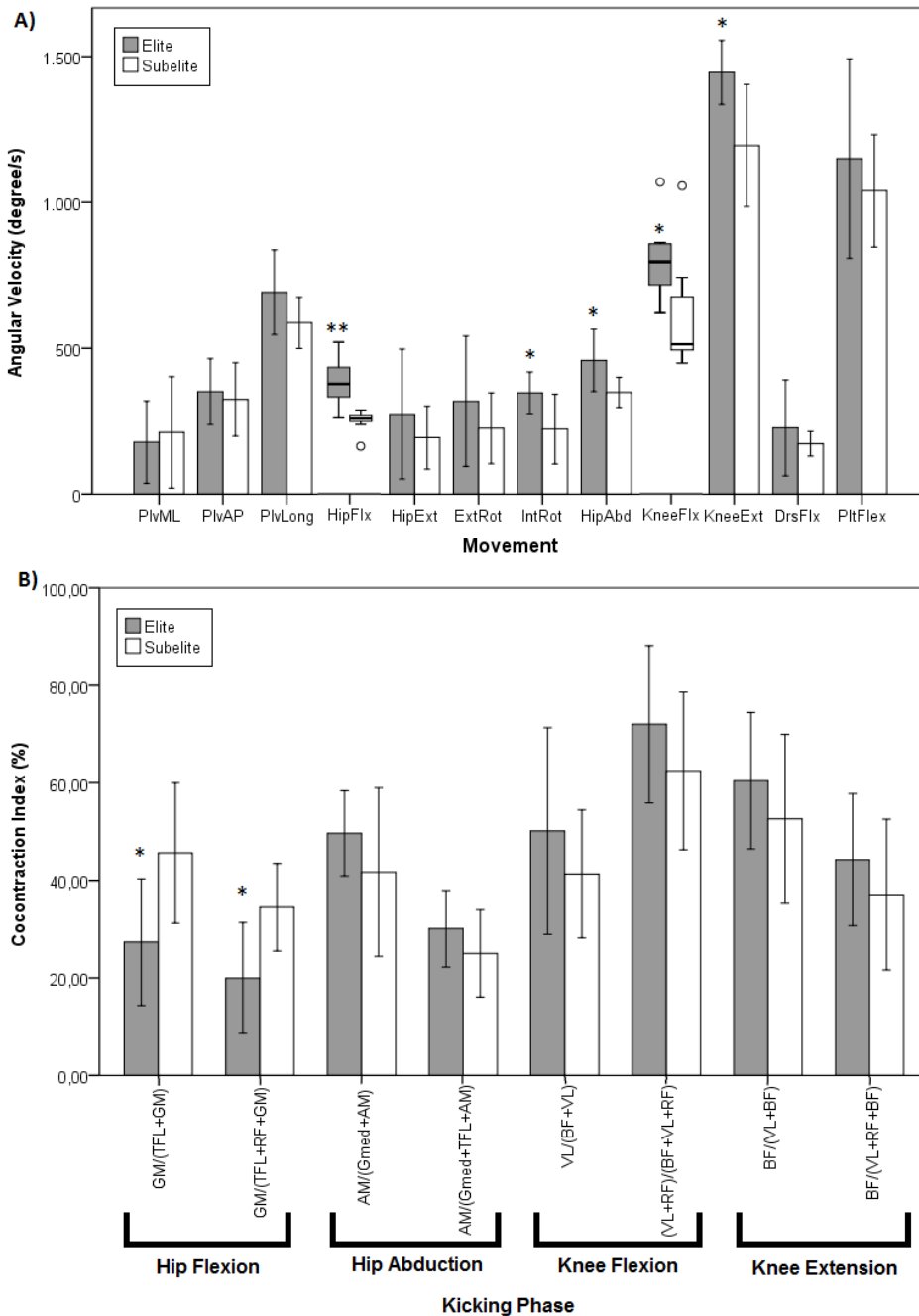


Figure 4. Comparative plots of angular velocity (A) and co-contraction index (B) between elite and sub-elite athletes. Bars represent means and error bars represent 95% of confidence intervals: * $p < 0.05$; ** $p < 0.01$; **DrsFlx** dorsiflexion; **PltFlex** plantar flexion; **KneeFlx** knee flexion; **KneeExt** knee extension; **HipFlx** hip flexion; **HipExt** hip extension; **Int Rot** internal rotation of the hip; **Ext Rot** external rotation of the hip; **Hip Abd**: hip abduction; **Piv** pelvis rotation; **ML** medium-lateral axis; **AP** antero-posterior axis; **Long** longitudinal axis; **GL** gastrocnemius lateralis; **VL** vastus lateralis; **RF** rectus femoris; **BF** biceps femoris; **AM** adductor magnum; **TFL** tensor fasciae lata; **GM** gluteus medium.

the combinations where the automatic onset was closest (with the lower type I and type II errors) to the visual onset. For this purpose, during various pilot tests, several combinations

of time windows (10 ms, 25 ms, 50 ms and 100 ms) and thresholds (1%, 2.5%, 5%, 7.5% and 10%) were tested. Qualitatively, Quinzi et al. [11] demonstrated that the EMG activation patterns

from the roundhouse kick showed low variability in combat sports athletes.

Statistical analysis

Statistical analyses were carried out using SPSS 18.0 (SPSS Inc., Chicago, USA). Shapiro Wilk test was used to analyse data normality and independent t-Student test to compare biomechanical indicators between groups. When there was no data normality assumption, Mann Whitney test was applied. The alpha level of significance was $p < 0.05$. Significant differences were quantified through Cohen's d score [25] to analyse the effect size of the comparisons; 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 [26].

RESULTS

For elite athletes, the peak velocity of pelvis, knee, ankle and foot were $M = 2.83$ m/s (95% CI [2.07, 3.59]), $M = 7.96$ m/s (95% CI [7.29, 8.63]), $M = 12.66$ m/s (95% CI [11.23, 14.10]) and $M = 16.29$ m/s (95% CI [14.68, 17.90]), respectively, while for sub-elite athletes they were $M = 2.75$ m/s (95% CI [2.18, 3.32]), $M = 6.91$ m/s (95% CI [5.58, 8.23]); $M = 11.36$ m/s (95% CI [8.69, 14.04]) and $M = 13.95$ m/s (95% CI [10.86, 17.05]), respectively. The independent t-test showed significant differences between groups of athletes for knee ($t^{(12)} = 3.66$, $p = 0.002$, $mean_{diff} = 1.05$ m/s, 95% CI [0.43, 1.68], $d = 1.40$), ankle ($t^{(12)} = 2.22$, $p = 0.023$, $mean_{diff} = 1.30$ m/s, 95% CI [0.02, 2.58], $d = 1.04$) and foot segment ($t^{(12)} = 3.47$, $p = 0.002$, $mean_{diff} = 2.38$ m/s, 95% CI [0.87, 3.80], $d = 1.36$), but not for pelvis ($t^{(12)} = 0.45$, $p = 0.33$, $mean_{diff} = 0.08$ m/s, 95% CI [-0.32, 0.48]).

Figure 3 shows bars of comparative analysis for kick time and premotor time. The elite athletes performed the kick with lower timing scores for almost all the timing indicators ($RT_{(Pelvis)}$: $t_{(12)} = -2.03$, $p = 0.032$, $mean_{diff} = -54$ ms, 95% CI [-113, 4], $d = 0.98$; PT : $t_{(12)} = -3.79$, $p = 0.001$, $mean_{diff} = -151$ ms, 95% CI [-237, -64], $d = 1.42$; KT : $t_{(7,7)} = -3.56$, $p = 0.004$, $mean_{diff} = -32$ ms, 95% CI [-52, -11], $d = 1.38$; TT : $U = 3$, $p = 0.003$, $d = 1.30$), except for the kinetic reaction time ($RT_{(GRF)}$: $U = 22$, $p = 0.375$). Only the premotor time of gastrocnemius lateralis ($t_{(12)} = -2.41$, $p = 0.016$, $mean_{diff} = -125$ ms, 95% CI [-237, 12], $d = 1.10$), gluteus maximum

($t_{(12)} = -2.3$, $p = 0.019$, $mean_{diff} = -120$ ms, 95% CI [-233, -8], $d = 1.08$) and vastus lateralis ($U = 9$, $p = 0.024$, $d = 0.97$) were lower in the elite athletes, compared to the sub-elite athletes.

Figure 4 shows comparative analysis of co-contraction indexes between groups of athletes obtained for biceps femoris and quadriceps (rectus femoris and vastus lateralis) muscles during the phases of knee flexion and extension; for gluteus maximum and hip flexor muscles (rectus femoris and tensor fasciae lata) during the phase of hip flexion and extension; for adductor magnum and hip abductor (gluteus medium and tensor fasciae lata) muscles during phase of hip abduction. Elite athletes demonstrated greater angular velocities for hip flexion ($t^{(12)} = 2.71$, $p = 0.001$, $mean_{diff} = 135$ °/s, 95% CI [57, 216], $d = 1.41$), internal rotation ($t^{(12)} = 2.19$, $p = 0.025$, $mean_{diff} = 124$ °/s, 95% CI [0.4, 248], $d = 1.03$) and abduction ($t_{(8,7)} = 2.27$, $p = 0.025$, $mean_{diff} = 110$ °/s, 95% CI [-0.2, 220], $d = 1.06$), and also for knee flexion ($U = 9$, $p = 0.024$, $d = 0.91$) and extension ($t_{(12)} = 2.59$, $p = 0.012$, $mean_{diff} = 251$ °/s, 95% CI [40, 461], $d = 1.15$). Moreover, sub-elites demonstrated superior co-contraction index than elite competitors for muscles that control the hip flexion (for GM with TFL: $t_{(12)} = -2.31$, $p = 0.040$, $mean_{diff} = -18.3$ %, 95% CI [-35.5, -1.01], $d = 1.07$; and for GM with TFL and RF: $t_{(12)} = -2.455$, $p = 0.030$, $meandiff = -14.5$ %, 95% CI [-27.4, -1.6], $d = 1.11$).

Elite competitors yielded higher ground reaction force peak in mediolateral ($U = 0$, $p = 0.001$, $d = 1.16$; elite: $Mdn = 22.54$, $IQR = 20.72-30.45$ %BW; sub-elite: $Mdn = 15.34$, $IQR = 11.47-16.9$ %BW), anteroposterior ($t^{(12)} = 2.39$, $p = 0.017$, $mean_{diff} = 22.9$ N, 95% CI [2.0, 43.8], $d = 1.09$; elite: $M = 80.3$, $SD = 8.6$ %BW; sub-elite: $M = 57.4$, $SD = 4.1$ %BW), vertical ($t^{(12)} = 2.18$, $p = 0.025$, $mean_{diff} = 56.6$ N, 95% CI [0.07, 103.2], $d = 1.03$; elite: $M = 196.4$, $SD = 23$ %BW; sub-elite: $M = 139.7$, $SD = 12.1$ %BW) and resultant ($t^{(12)} = 2.23$, $p = 0.023$, $mean_{diff} = 62.1$ N, 95% CI [1.5, 122.8], $d = 1.04$; elite: $M = 213.0$, $SD = 24.8$ %BW; sub-elite: $M = 150.9$, $SD = 12.7$ %BW) axis than sub-elite athletes. Elite athletes also presented superior performance in the rate of force development ($U = 4$, $p = 0.004$, $d = 0.96$; elite: $Mdn = 2116$, $IQR = 972-3451$ %BW · s⁻¹; sub-elite: $Mdn = 399.0$, $IQR = 360-710$ %BW · s⁻¹).

DISCUSSION

The major findings obtained in the present study were as followed: (a) timing indicators and selected electromyographic cocontraction indexes were significantly lower in elite group compared to sub-elite group; (b) linear (toe, ankle and knee) and angular (knee and hip) peak velocities were significantly higher in elite than in sub-elite group; (c) elite athletes performed the preparation phase with superior magnitudes of force and rate of force development.

It was found that elite taekwondo athletes had a faster time in kicking phase and total time, reaching higher lower limb linear velocity than sub-elite athletes. Kick velocity and kicking timings are central indicators because power and kinetic energy of impact are determined by velocity [4] and because to score the athlete needs to be faster than the opponent [1, 8, 27]. In our results, there was no difference in the kinetic reaction time ($RT_{(GRF)}$), but elite athletes produced force more explosively, reaching a higher peak of force, mainly in the horizontal plane. The superior magnitude of the force and the more explosive preparation phase obtained by our elite athletes can explain why elite athletes did start to move the pelvis earlier than sub-elite athletes, and why the preparation phase was shorter in this group, characterising a more efficient impulse. It can also partially explain why elite athletes were faster, as researchers [6, 20] found significant correlations between GRF indicators and execution time (inverse correlations), and linear peak velocities (direct correlations) of the pelvis, thigh, shank and foot. Thus, according to these authors, as much force an athlete press against the ground, the faster the kick will be.

Due to their respective kinesiologic action, i.e. plantar flexion, knee extension and hip extension [28], gastrocnemius lateralis, vastus lateralis and gluteus maximum are important muscles to propel the pelvis forward in the fighting posture. In elite athletes, these muscles had lower premotor time compared to sub-elite athletes. This means that these muscles activated first in the athletes of higher level, contributing to generate a more efficient pattern of impulse against the ground, i.e. a lower time of preparation phase with superior ground reaction peak of forces and rate of force development. Chung and Ng [19] demonstrated that professional taekwondo athletes had lower premotor time

than amateurs or non-athletes for sport-specific stimulus (a photograph of an athlete performing a sidekick attack motion), but it did not occur for simple visual and auditory stimulus. The opposite happened for non-specific stimulus, i.e. the professional group responded slower than non-professional, indicating the ability of professional athletes to focus on relevant stimulus from the combat, decreasing the sensibility to irrelevant stimulus. Our stimulus was artificial (LED), but the data collection scene was prepared in order to approximate from the ecological validation since the simulated opponent (dummy) had physical similarity in appearance of a real opponent. Furthermore, we used the official trunk, and head protectors, the stimulus and the target, were placed in fight relevant body parts from the dummy, in a selective reaction time design and the reaction movement analysed was specific to a taekwondo match.

Another coordinative pattern that did suffer influence from the expertise level was the co-contraction index. The higher co-contraction of hip muscles, found in athletes of the inferior level, could have influenced the efficiency of hip flexion acceleration. Accordingly, the elite athletes reached the higher magnitude of angular velocity in hip flexion. This also happened in the hip internal rotation, hip abduction, knee flexion and knee extension. The higher co-contraction between GM and TFL found in sub-elite athletes might explain the lower hip internal rotation velocity in sub-elite athletes considering, respectively, the external and the internal rotator role of the GM and TFL muscle [28, 29]. In the calculation of the co-contraction index, it was used the following equation: $\text{Index of Co-contraction} = \text{GM} / (\text{TFL} + \text{GM})$, what means that a higher co-contraction index is caused by a combination of high level of GM activity and low-level TFL activity. Then, a minor activity of TFL or a greater activity of GM can negatively influence the internal rotation speed [29]. In the roundhouse kick, the hip abduction depends on a combination of hip flexion and internal rotation [8, 30]. In the same way, faster hip flexion contributes to generate a faster knee flexion, due to the known phenomenon of motion dependent moment [31], especially if we consider that similarly to Thibordee and Prasartwuth [12] there was no difference in the co-contraction index of muscles that controls knee joint.

Another important result was the higher angular velocity of knee extension found in

elite athletes. This can be explained by the combination of higher velocities in the knee and hip flexion. Higher knee flexion velocity could have resulted in higher level of tendon elastic energy of quadriceps [32, 33], while higher hip flexor velocity could have generated a higher hip angular momentum to be transmitted to the knee joint [7]. For taekwondo athletes, Sørensen et al. [7] demonstrated that in “frontal kick”, 64% from the positive angular momentum and consequently the angular velocity of the lower leg are transmitted from the momentum caused by the angular velocity of thigh segment. Similarly to the frontal kick [7], the roundhouse kick is a technique known by the “proximodistal” transmission of momentum [6, 30].

The findings provided in this study should be considered in the framework of the following limitation, given the small sample sizes, some non-significant results may be related to a lack of statistical power, then, the negative findings should be interpreted with caution. However, the small sample size was compensated by the selective sample composition, mainly for the elite group. Furthermore, the fact that the sample size obtained was not much higher than the number stated by the sample calculation associated with the fact that all significant results in statistical comparisons had high effect sizes (Cohen’s $d = 0.91$ to 1.42), provided a protective factor against the type I errors, which could be associated with the large number of indicators analyzed.

The presented results allow us to recommend that a) to shorten the preparation phase time of sub-elite athletes, coaches should develop training methods aiming to improve the leg strength and rate of force production through kinesiological

specific activities (e.g. kick with elastic bands attached to the waist) for overload this phase; b) coaches should focus on speed training for to improve knee, ankle and foot linear speed, and develop exercises aiming to turn faster the knee flexion/extension and hip angular movements (flexion, abduction and medial rotation).

CONCLUSIONS

Elite athletes performed the kicks with lower reaction time, impulse and kicking phase. Furthermore, they also presented a higher level of linear velocities, associated with higher ground reaction forces, which resulted in a more efficient impulse phase than the sub-elite athletes. The superior linear velocities of lower segments, found in elite athletes were accompanied by higher angular velocities of hip and knee joints, which in turn, were related to the lower level of co-contraction of muscles that control the hip flexion movement.

The specific neuromuscular and technical differences between groups found in this study indicate that to improve the performance of sub-elite athletes these indicators could be useful in monitoring their training status. Furthermore, based on the results of this study we conclude that starting to contract specific muscles early and to perform the kicking phase with the gluteus maximum more relaxed is associated with a more efficient high kick performance. If a coach uses this information to design specific training methods, there could be a potential to improve the kick performance of the athletes.

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