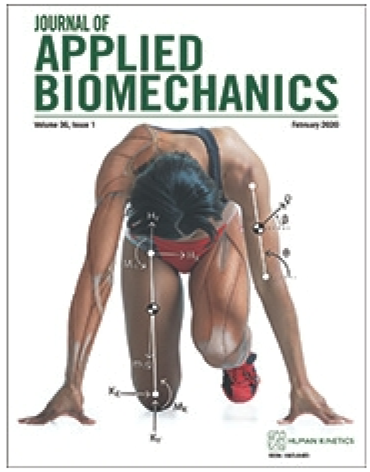

Inter-joint coordination in kicking a moving target: a comparison between elite and non-elite taekwondo players

Journal:	*Journal of Applied Biomechanics*
Manuscript ID	JAB.2020-0359.R2
Manuscript Type:	Original Research
Keywords:	biomechanics, exercise performance, kinematics, motion analysis, motor control, sport

TITLE PAGE

July 19, 2021

JAB.2020-0359.R2

Title:

Inter-joint coordination in kicking a moving target: a comparison between elite and non-elite taekwondo players

Bruno G. Straiotto[1], David P. Cook[1,2], Darren C. James[1], P. John Seeley[1]

[1]School of Applied Sciences, London South Bank University, 103 Borough Road, London SE1 0AA, United Kingdom.

[2]National Taekwondo Team Norway, Trygve Nilsens Vei 28D, 1061 Oslo, Norway.

Conflict of Interest Disclosure: None.

Correspondence Address:

Bruno G. Straiotto, PhD

School of Applied Sciences

London South Bank University

103 Borough Road, London SE1 0AA

United Kingdom

Phone: +44 20 7815 7038; Email: brunostraiotto@gmail.com

Running Title: Inter-joint coordination in kicking

Abstract

Patterns of inter-joint coordination in the kicking legs of taekwondo players were investigated to understand movement pattern variability as a functional property of skill level. Elite and non-elite players performed roundhouse kicks against a custom-built moving target fitted with an accelerometer, and movements were recorded by motion capture. Average foot segment velocities of 13.6 $m.s^{-1}$ and 11.4 $m.s^{-1}$ were recorded for elite and non-elite players respectively ($p < 0.05$), corresponding to target accelerations of 87.5 **g** and 70.8 **g** ($p < 0.05$). Gradient values derived from piecewise linear regression of CRP curves established the comparative incoordination of non-elite taekwondo players in the form of an overshoot behaviour during the crucial period leading to target impact ($p < 0.05$). This overshoot was apparent in both knee-hip and ankle-knee CRP curves. Elite players generated greater limb speed and impact force through more effective limb segment coordination. The combination of CRP and piecewise linear regression techniques allowed identification of alternate joint control approaches in the two groups.

Keywords: Continuous relative phase, piecewise linear regression, roundhouse kick, variability

Word count: 3996

Introduction

Human movement variability and the complex manner in which skills and coordination alter over time pose challenges in describing and analysing human movement systems. The multiple degrees of freedom of the body in motion allow for a broad range of movement patterns and strategies.[1] Studies of motor control from the perspective of dynamical systems theory indicate that variability in movement is important for changes in coordination to occur and assists learning of new movements through identification of variations in relevant parameters.[2] The continuous relative phase (CRP) technique provides a measure of the coordinative interaction of two segments or joints throughout the entire movement cycle, and allows evaluation of the adaptability of coordination patterns.[3–5] CRP is obtained from the difference in phase angle of two predominantly oscillatory movements.[6] The relative phase angle is constructed from the state space of the respective position and velocity phase portraits for each segment or joint.[7] The main advantage of CRP is that it combines four variables - displacements and velocities of proximal and distal joints - into one measure.[2]

Kicks are the primary attacking skills in martial arts disciplines since kicking transfers a much larger impact to an opponent than punching.[8,9] The roundhouse kick has previously been identified as the most commonly used kick in martial arts competitions such as karate, muay thai and taekwondo and several fundamental movement patterns and techniques are held in common for roundhouse kick movement.[10] Central shared characteristics are swift pelvic axial rotation, hip abduction, and high knee flexion and extension velocities, combined with rapid movements of the centre of mass in approach to target.[10] O'Sullivan et al[11] compared characteristics of taekwondo and yongmundo players' roundhouse kicks. They found quite small differences between peak impact forces according to the height of the target (6400 vs 6393 N for mid-level and 5419 vs 5475 N for high targets, for taekwondo and yongmundo players respectively).[11] Lee[12] found the medio-lateral displacement of the centre of mass in taekwando players was much smaller than for hapkido players. According to Lee[12], smaller medio-lateral displacement of the body centre of mass in taekwondo players is associated with limited movement of the trunk, which permits a faster defensive response against an opponent player.

The roundhouse kick has previously been identified as the most commonly used kick in taekwondo, accounting for approximately 63% of kicks used by taekwondo players during competition and 89% of total points scored.[9,13] Biomechanical characteristics of the kick include end velocities at the foot ranging from 11 to 17 $m.s^{-1}$, [9,14–16] and impact forces in excess of 6 kN.[11,14,17,18] However, these measurements provide no insight into how a roundhouse kick is performed and lack the precision with which to categorise expert proficiency.

Estevan et al[19] and Quinzi et al[20] presented the only studies that have explicitly addressed the coordination pattern of the roundhouse kick in elite players. Estevan et al[19] showed greater variability when athletes had to kick from an initial stance position they were not accustomed to, and it was suggested that this indicated the adaptability of the athletes' execution technique. Quinzi et al[20] noted a significant shift in coordination pattern when comparing roundhouse kicks without a target and to a target. Neither study addressed player skill acquisition as taekwondo experience accumulated and therefore provided no insight into how training might operate to improve kicking performance. To date, no published studies have reported on Bernstein's concepts of operation of degrees of freedom related to spatiotemporal coordination of the roundhouse kick in particular, i.e. both freeing degrees of freedom with training associated with the development of functional coupling and constraining abundant degrees of freedom for control.

This study attempts to gain insight into skill acquisition in ecologically-valid moving-target kicking for elite and non-elite taekwondo players using CRP in combination with piecewise linear regression. The latter method splits the range of a variable into intervals and fits a linear function to data for each interval.[21] This was used to determine differences between elite and non-elite players in the temporal organisation of CRP data and how they operate in dynamic performance environments. The tools used in this study could bridge a communication gap between coaches and scientists. In summary, the over-arching aim of this paper is to understand movement pattern differences as a functional property of the level of skill of taekwondo players. We hypothesised differences in leg coordination patterns between elite and non-elite taekwondo players, particularly in the target approach phase of the kick. Specifically, we hypothesised that CRP measures of limb segment relations would reveal differences in coordination between players of different skill levels.

Methods

Taekwondo players were recruited for this study: elite (8 males and 1 female; age 27.0 ± 0.4 yr; mass 74 ± 1 kg; height 1.7 ± 0.1 m) and non-elite (9 males; age 35.0 ± 0.1 yr; mass 86 ± 3 kg; height 1.8 ± 0.1 m). (Measures expressed as mean ± SEM throughout.) The elite taekwondo players had practised taekwondo for more than eighteen years (18.8 ± 1.5 yr) and had competed at a minimum of A-class international and national levels across all taekwondo weight categories for a minimum of eight years (8.3 ± 1.0 yr). The non-elite taekwondo players had practised Taekwondo for a shorter period of time (3.2 ± 0.2 yr), had trained at a recreational level and competed with experience of approximately one year (1.6 ± 0.5 yr). The experimental protocol was given approval by London South Bank University Research Ethics Committee and all players provided written informed consent prior to taking part in the study.

Main testing took place on a target stage (Figure 1). This was a 2.5 m × 2.5 m raised platform with a 0.5 m × 0.5 m space cut from one edge to accommodate a kicking bag target (Figure 1a). The stage was covered with martial arts matting to ensure sufficient friction against the players' feet during operation of the experimental protocol. The kicking bag was secured in a hemispherical base filled with 75 kg of concrete and coated with rubber (Figure 1c). A commercially available kicking bag (Body Sculpture, Bradford, UK), made from high-density plastic foam and encased in a durable vinyl cover, served as the target (Figure 1b).

[Insert Figure 1 about here]

The players did eight to twelve practice trials (elite 9.2 ± 0.1, non-elite 9.4 ± 0.1) to become comfortable with markers placed on their skin and familiar with the procedure. The players were then asked to perform five roundhouse kicks (Figure 2). The player was instructed to move backwards and forwards on the command "*1-2*" and to initiate a roundhouse kick with the back leg soon after the word *"PLAY"* appeared on a screen (Figure 1d).

The target was drawn to one side for each roundhouse kick trial and was released at the moment *"PLAY"* appeared on the screen. Small variations in the starting position of the target and the starting position of the taekwondo player combined with the hemispheric target base and the lack of cylindrical symmetry of the target meant that the trajectories of the target and the kicks produced by the players were not identical to one another, though broadly similar.

[Insert Figure 2 about here]

Target acceleration data were captured using a 1000 **g** triaxial accelerometer (Kistler 8763B1KB, Amherst, NY, USA). The acceleration data were digitally filtered with a low-pass Butterworth 4-channel coupler (Kistler, Type 5134). The signals from the coupler were sent to a PC-based data acquisition system (Qualisys Track Manager, Qualisys AB, Sweden) at a sampling rate of 1000 Hz per channel.[15] The cut-off frequency for the acceleration signal was 200 Hz.[22] The accelerometer was rigidly fixed inside the kicking bag at the midpoint on a 6.0 cm × 4.0 cm aluminium plate secured to the inside by four self-tap screws (Figure 1e-f). The accelerometer position was the target point for the taekwondo player (Figure 1a) with the height of that point selected by each player during their familiarisation period. This was arranged by shifting the height of the kicking bag on the target post (Figure 1a). Roundhouse kick movements were recorded using reflective markers of 12 mm diameter attached to the skin by double-sided adhesive tape on relevant anatomical landmarks according to Collins et al[23] with slight modification to suit this research (Table 1). Kinematic data were acquired using an eight-camera motion-analysis system (Oqus 3-series, Qualisys AB, Gothenburg, Sweden) sampling at 500 Hz.

[Insert Table 1 about here]

Data analysis had four main steps: (i) building an articulated lower-limb system in order to derive segment centre of mass velocities and joint angles; (ii) specification of roundhouse kick movements in terms of instants and periods in order to progress the analysis and relate these to the peak resultant target acceleration; (iii) calculation of CRP phase values, mean absolute relative phase and deviation phase; and (iv) use of piecewise linear regression to determine the temporal structure of CRP curves.

(i) Inverse kinematics was applied to a seven-segment model for each player (pelvis, thighs, shanks and feet) using Visual3D software (C-Motion Inc, Germantown, MD, USA). Joint constraints were enforced such that segments could rotate with three degrees of freedom, but not translate with respect to the adjacent segment.[24]
Segment centre of mass velocities were measured from the global coordinate system and sagittal plane joint angle displacements were defined by a Cardan rotation sequence (XYZ) with respect to a distal frame of reference, with the exception of the pelvis angle, which was defined relative to the global coordinate system.[25] Winter's residual analysis technique and fourth-order low-pass Butterworth filters were used to smooth data (cut-offs of 8, 10 and 12 Hz for hip, knee and ankle respectively).[26]

(ii) Three instants were defined for the kicking leg for each roundhouse kick: toe-off (TO), maximum knee flexion (MF) and impact (IM, Figure 2). The minimum value of the anteroposterior component of the foot segment trajectory defined TO; IM was taken to correspond to the peak resultant acceleration of the target. Two periods were defined from these instants: Release (TO-MF) and Impact (MF-IM). Each movement period was interpolated to 101 points in order to normalise different kicking cycles. The peak velocities of segment centres of mass for TO-MF and MF-IM and the peak resultant target acceleration were calculated using Visual 3D.

(iii) Phase plots for the hip, knee and ankle joint were created by plotting angular velocity as a function of the angular displacement in the sagittal plane.[20] The angular displacements and velocities were normalised to a range -1 to +1 according to Li.[27] The phase angle for each joint at each data point was then calculated from the portrait trajectory.[4] The CRP angles for knee-hip and ankle-knee joint couplings were calculated as the difference between the distal and proximal joint phase angles.[2] This was subsequently expressed as a single measure - mean absolute relative phase - to summarise the overall phase relationship.[29] A higher mean absolute relative phase value reflects joints having more of an out-of-phase relationship; lower mean absolute relative phase reflects joints having a more in-phase relationship.[5,30] The deviation phase served to define the stability of the coupling.[2] A high deviation phase value indicates variable, relatively unstable, movement relations for the paired joints and vice versa.[28] All data were calculated using custom code written in MATLAB 2013a (MathWorks Inc, Natick, MA, USA).

(iv) Piecewise linear regression was applied to the time courses of knee-hip and ankle-knee CRP data for each kick and for the kick periods TO-MF and MF-IM. Each kick period was normalised to 101 data points and each time course was divided into five phases of 20 data points with 10 "knot" data points defining the start and end of each phase (Figure 3). The number of knot data points was established through a trial-and-error approach and numbers of knots were constant across kicks. Phase 1 was delimited by knots at data points 1 and 20, phase 2 by knots at 21 and 40 and so forth. Five phases summarised the time courses effectively and illustrated the contrasts between the two groups' CRP trajectories. The phases might have been of different lengths but keeping to equal lengths achieved desirable simplicity. The piecewise linear regression model for each phase was represented by an equation derived from least squares linear regression (Figure 3). In this way each CRP curve was summarised in terms of 10 parameters (the gradients and intercepts of the fitted lines) and the temporal development of the kicks could be directly compared between elite and non-elite groups. The least squares fits were carried out using MATLAB (Figure 3).

[Insert Figure 3 about here]

Statistical analysis: The primary significance level was set at α = 0.05. Kinematics, mean absolute relative phase, deviation phase and piecewise linear regression gradient data were checked for outliers and normality for both groups using the Kolmogorov-Smirnov test (all $p > 0.05$) and there was homogeneity of variance as evaluated by Levene's test (all $p > 0.05$). Therefore univariate ANOVA was employed to determine the differences between elite and non-elite taekwondo players for segment velocities for each period. A mixed model repeated measures ANOVA with skill level (elite vs non-elite) as the between-subjects factor was used additionally to identify main and interaction effects in piecewise linear regression gradients. Bonferroni-adjusted post-hoc tests were used when significant effects were noted. Effect sizes (η^2) were also calculated. SPSS software (version 21, SPSS Inc, Chicago, IL, USA) was used for all statistical tests.

Results

Higher velocities for the segment centre of masses were noted in the approach to contact (period MF-IM compared with period TO-MF) for both groups, and there was a progressive increase in maximum velocity from the most proximal to the most distal segment (Table 2). The elite players had higher segment centre of mass velocities for the two periods and for all segments; however, significant group differences were only found for the shank during TO-MF ($F_{(1, 52)} = 29$, $p = 0.001$, $\eta^2 = 0.21$) and MF-IM ($F_{(1, 52)} = 17$, $p = 0.001$, $\eta^2 = 0.24$), and for the foot during MF-IM ($F_{(1, 52)} = 19$, $p = 0.001$, $\eta^2 = 0.29$). In addition, peak resultant target accelerations were significantly higher for the elite players (87.5 ± 4.1 **g**) than their non-elite counterparts (70.8 ± 2.8 **g**; $F_{(1, 52)} = 30$, $p = 0.01$, $\eta^2 = 0.36$).

[Insert Table 2 about here]

CRP curves for elite and non-elite taekwondo players, averaged over all players in the group, had broadly similar CRP patterns for the two time periods and both coupling profiles (knee-hip, ankle-knee; Figure 4). The maxima and minima of the curves are marked on the graphs. For non-elite TO-MF and elite TO-MF and MF-IM these extrema lie at the ends of the periods, i.e. at data points 1 and 101. For non-elites for the crucial MF-IM period, the maxima are significantly distant from the ends of the relevant periods, indicating overshoots in relative joint movements for non-elite players. The point of inflection time-wise is earlier for non-elite than elite and the gradient at the inflection point is higher for non-elite players: non-elite relative joint movements are premature and overly rapid when compared to higher-impact elite kicking. In both groups there is a positive gradient of the knee-hip CRP curve for both periods (Figure 4a-b). This indicates the knee joint is moving faster in phase space with respect to the hip joint. The ankle-knee CRP curves show similar patterns for both groups and periods (Figure 4c-d). However, the gradients of curves in the ankle-knee coupling are opposite to those for the knee-hip coupling, indicating the knee joint is moving faster in phase space than the ankle joint.

[Insert Figure 4 about here]

Significant differences in piecewise CRP gradients for ankle-knee and knee-hip couplings were revealed by ANOVA (phases [1 to 5] and skill level as main factors). This was the case for both movement periods (all $p < 0.05$; Figure 5). Significant differences were also found in the interaction between group and phase for the gradient of knee-hip and ankle-knee CRPs for MF-IM ($F_{(1.5, 66.8)} = 110$, $p = 0.002$, $\eta^2 = 0.21$ and $F_{(1.3, 67.7)} = 6.1$, $p = 0.01$, $\eta^2 = 0.11$

respectively). All of the differences above were statistically significant for ANOVA with skill level (elite vs non-elite) as the between-subjects factor: gradients for knee-hip and ankle-knee CRP for MF-IM ($F_{(1, 52)} = 8.4$, $p = 0.007$, $\eta^2 = 0.16$ and $F_{(1, 52)} = 22$, $p = 0.001$, $\eta^2 = 0.31$ respectively). Bonferroni post-hoc tests revealed the knee-hip differences were significantly different between the first and subsequent phases ($p < 0.05$) for MF-IM, the only exception being knee-hip CRP during MF-IM for phase 1 vs 4 ($p = 1.0$). Bonferroni post-hoc tests for the gradient ankle-knee CRP revealed a significant effect between all phase pairs ($p < 0.05$) with the exception of phase 1 vs 4 ($p = 0.99$). The elite and non-elite taekwondo players produced broadly similar gradient patterns for the two periods for both knee-hip and ankle-knee CRP (Figure 5). However, absolute values of the gradient were lower for both knee-hip and ankle-knee for elite players during MF-IM, reflecting smoother movement transitions for the elite in the approach to impact.

[Insert Figure 5 about here]

No statistically significant differences were found between the two taekwondo groups for knee-hip or ankle-knee mean absolute relative phase and deviation phase values (all $p > 0.05$; Figure 6).

[Insert Figure 6 about here]

Discussion

The purpose of this work was to investigate lower body joint coupling during roundhouse kick movement in elite and non-elite taekwondo players in order to gain insight into skill acquisition and, hence, potential to identify points of focus for training early-stage taekwondo players in improving kicking technique. Maximum velocities of the kicking foot were on average 20% greater for the elite group and corresponding linear target accelerations were 24% greater. The combination of CRP and piecewise linear regression methods identified differences in the temporal structure of coordination between elite and non-elite groups. The gradient values derived from piecewise linear regression of CRP for non-elite taekwondo players established overshoot behaviour in their approach to target impact. The elite players move leg joints progressively during the crucial period leading to impact.

Bernstein[31] proposed that development of skill would involve the gradual unfreezing of degrees of freedom and this, in relation to limb segments and this study, was hypothesised to occur in a proximal to distal sequence. Later in the learning process, once the performer has achieved mastery of redundant degrees of freedom over the skill, more efficient solutions to the degrees of freedom problem would be used.[31] Specifically, joints, segments, muscles and motor units would be turned into goal-directable systems. The analysis of spatiotemporal coordination of the roundhouse kick for this study supports this view, particularly in the target-approach phase of the kick. Our results suggest that non-elite taekwondo players are not able to exert fine control over abundant degrees of freedom. For example, from piecewise linear regression measures, non-elite taekwondo player movements were comparatively "asymmetrical" whereas elite movements were steadily progressive and "smooth" in pattern during the period to impact.

Mean absolute relative phase and deviation phase measures failed to discriminate between the movement patterns of the two groups. In contrast, piecewise linear regression, which divided each of the periods TO-MF and MF-IM into five phases, and averaging after regression permitted discrimination between the coordination patterns of the two groups.

In our research, elite taekwondo players activated kinematic synergies needed for the task whereas non-elites, whilst demonstrating an ability to operate the essentials of the task, were not able to combine synergies into an optimal overarching movement. The learning situation under study produced comparable results to other investigations: reference, for example, the reduction in active degrees of freedom at joint level recorded by Broderick and Newell[32] in relation to bouncing a basketball. Correspondingly, elite taekwondo players (arguably) reduced degrees of freedom of the limb for the roundhouse kick movement to a single unit (Figure 5) and generated higher average foot centre of mass velocities and forces in approach to impact (13.6 $m.s^{-1}$ and 87.5 **g**, compared to non-elites with values of 11.4 $m.s^{-1}$ and 70.8 **g**). Whilst we did not pursue normalisation of target accelerations to the body masses of participants, we note that, given the lower average mass of elite players (74 versus 86 kg), such normalisation would increase the difference between group-wise accelerations. Centre of mass segment velocity of the foot of elite taekwondo players agreed very well with previous studies (11.9 to 14.8 $m.s^{-1}$).[9,15] The target accelerations for elite taekwondo players observed in this study are lower than the previously reported results of 130 **g**.[15] An explanation for this difference may lie in the type of target (Hybrid II head and neck) employed by Fife et al[11] since the target used in this study was much heavier.

The dynamical systems theory approach to lower extremity coordination using the CRP technique provides a measure of the coordinative interaction of knee-hip and ankle-knee joint pairs throughout the entire movement cycle, and allows evaluation of the adaptability of coordination patterns. However, CRP did not capture variations in the way in which the motor behaviour developed over time, in this case the roundhouse kick. Piecewise linear regression proved a simple method to quantify this, making hidden coordinative behaviour explicit as movement variation over time and between groups.

Competitive performance is intrinsically linked to the inter-related characteristics of the performer-environment system (e.g. permitted rule sets, opponent dynamics, performance boundaries, external stimuli and individual biophysical properties).[33] Such a performance ecology has the potential to flow from relatively predictable game-play to game-play as an "adaptive readiness to respond to emerging information".[34] The present study would indicate that non-elite performers were unable to control effectively their respective coordinative patterns when faced with a *dynamic* target environment, i.e. emerging target information.

Therefore to foster taekwondo player development toward the elite level it seems desirable to introduce and orchestrate a dynamic element of representative design into taekwondo training environments and tasks. In doing so, taekwondo players should be presented with task affordances that enable a large area of task space to be explored and gradual unfreezing of degrees of freedom in the proximal to distal sequence.[31] This in turn enables the player to experiment with synergistic couplings through a range of movement solutions, fostering smooth, adaptive responses in the control mechanisms underpinning kicking motion. Woods et al[35] refer to this as a "process of attunement to performance opportunities" which assists in development of functionally adaptable relationships (i.e. kick-to-target).

There are limitations to this study. The use of angular velocity may propagate errors due to soft tissue artefacts and those associated with the recording system, thus increasing uncertainty in the CRP data. The effects of these sources of error were, however, minimised via joint constraints (translation restraints related to inverse kinematics and differential filtering) and it is quite unlikely that such issues would result in differential effects between subject groups. The pattern and variability of inter-joint coordination of the kicking motion were only examined in the sagittal plane on the basis that the major portion of work was performed in this plane.[20,36,37] The accelerometer inside the kick bag may register small changes in target dimensions not directly related to the force of impact (noise); however, this problem was minimised by placing the accelerometer near the target point and signal filtering.

Our findings illustrate differential use of dynamical degrees of freedom between elite and non-elite taekwondo players, which supports Bernstein's view.[31] Given that kicking was against a moving target, this suggests that elite players have the ability to freeze and release degrees of freedom as needed (i.e. conversion to a controllable system)[31] whereas non-elite players do not have such detailed control. From the perspective of dynamical systems theory, elites developed a movement pattern for which the variability was functional and consequently generated higher terminal segment velocities and peak resultant target accelerations. The combination of CRP and piecewise linear regression methods enhanced understanding of this complex coordinated movement. Future studies that combine these analyses of lower body motion with those of the upper body may enhance understanding of skills differences between player groups and further contribute to coaching development in motor control of complex movements.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

1. Bernstein NA. On dexterity and its development. In: Latash ML, Turvey MT, eds. *Dexterity and Its Development*. Mahwah, New Jersey: Lawrence Erlbaum; 1996:3-244.
2. Kurz MJ, Stergiou N. Applied dynamic systems theory for the analysis of movement. In: Stergiou N, ed. *Innovative Analyses of Human Movement*. Leeds (UK): Human Kinetics; 2004:93-119.
3. van Emmerik REA, Wagenaar RC. Effects of walking velocity on relative phase dynamics in the trunk in human walking. *J Biomech*. 1996;29(9):1175-1184. doi:10.1016/0021-9290(95)00128-X
4. Hamill J, van Emmerik REA, Heiderscheit BC, Li L. A dynamical systems approach to lower extremity running injuries. *Clin Biomech*. 1999;14(5):297-308. doi:10.1016/S0268-0033(98)90092-4
5. Byrne JE, Stergiou N, Blanke D, Houser JJ, Kurz MJ, Hageman PA. Comparison of gait patterns between younger and elderly women: an examination of coordination. *Percept Mot Skills*. 2002;94(1):265-280. doi:10.2466/PMS.94.1.265-280
6. Peters BT, Haddad JM, Heiderscheit BC, Van Emmerik REA, Hamill J. Limitations in the use and interpretation of continuous relative phase. *J Biomech*. 2003;36(2):271-274. doi:10.1016/S0021-9290(02)00341-X
7. MacLean C., van Emmerik REA, Hamill J. Influence of a custom foot orthotic intervention on lower extremity dynamics in healthy runners. *Clin Biomech*. 2006;21(6):623-630. doi:10.1016/j.clinbiomech.2006.01.005
8. Szczęsna A, Błaszczyszyn M, Pawlyta M. Optical motion capture dataset of selected techniques in beginner and advanced Kyokushin karate athletes. *Sci Data*. 2021;8(1). doi:10.1038/s41597-021-00801-5
9. Kim YK, Kim YH, Im SJ. Inter-joint coordination in producing kicking velocity of Taekwondo kicks. *J Sport Sci Med*. 2011;10(1):31-38. doi:10.1016/j.humov.2017.05.005
10. Gavagan CJ, Sayers MGL. A biomechanical analysis of the roundhouse kicking technique of expert practitioners: A comparison between the martial arts disciplines of Muay Thai, Karate, and Taekwondo. *PLoS One*. 2017;12(8). doi:10.1371/journal.pone.0182645

11. O'Sullivan D, Chung C, Lee K, et al. Measurement and comparison of taekwondo and yongmundo turning kick impact force for two target heights. *J Sport Sci Med*. 2009;8:10-13.
12. Lee K-K. The Effect of Target Height on Kinematics of Round Kick in Taekwondo and Hapkido. In: Blackwell JR, Sanders RH, eds. *Proceedings of the 19th International Conference on Biomechanics in Sports*. San Francisco: International Society of Biomechanics in Sports; 2001:162-165.
13. Kwok HHM. Discrepancies in fighting strategies between Taekwondo medalists and non-medalists. *J Hum Sport Exerc*. 2012;7(4):806-814. doi:10.4100/jhse.2012.74.08
14. Conkel BS, Braucht J, Wilson W, Pieter W, Taaffe D, Fleck SJ. Isokinetic torque, kick velocity and force in Taekwondo. *Med Sci Sport Exerc*. 1988;20:S5.
15. Fife G, Pieter W, O'Sullivan D, Cook D, Kaminski T. Effects of olympic style taekwondo kicks on an instrumented head-form and resultant head injury measures. *Br J Sport Med*. 2011;45(4):318-319. doi:10.1136/bjsm.2011.084038.25
16. Serina ER, Lieu DK. Thoracic injury potential of basic competition taekwondo kicks. *J Biomech*. 1991;24(10):951-960. doi:10.1016/0021-9290(91)90173-k
17. 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(3):242-248. doi:10.1016/j.jbiomech.2008.10.041
18. Pieter F, Pieter W. Kinematics and Kinetics of Taekwon-do Side Kick. *Biol Sport*. 1995;12(4):257-266. doi:10.2478/v10078-011-0068-z
19. Estevan I, Freedman Silvernail J, Jandacka D, Falco C. Segment coupling and coordination variability analyses of the roundhouse kick in Taekwondo relative to the initial stance position. *J Sports Sci*. 2016;34(18):1766-1773. doi:10.1080/02640414.2015.1137342
20. Quinzi F, Sbriccoli P, Alderson J, Di Mario A, Camomilla V. Intra-limb coordination in karate kicking: Effect of impacting or not impacting a target. *Hum Mov Sci*. 2014;33(1):108-119. doi:10.1016/j.humov.2013.07.021
21. Lin JFS, Karg M, Kulic D. Movement Primitive Segmentation for Human Motion Modeling: A Framework for Analysis. *IEEE Trans Human-Machine Syst*. 2016;46(3):325-339. doi:10.1109/THMS.2015.2493536
22. Buśko K, Staniak Z, Szark-Eckardt M, et al. Measuring the force of punches and kicks among combat sport athletes using a modified punching bag with an embedded accelerometer. *Acta Bioeng Biomech*. 2016;18(1):47-54. doi:10.5277/ABB-00304-2015-02
23. Collins TD, Ghoussayni SN, Ewins DJ, Kent JA. A six degrees-of-freedom marker set for gait analysis: Repeatability and comparison with a modified Helen Hayes set. *Gait Posture*. 2009;30(2):173-180. doi:10.1016/j.gaitpost.2009.04.004
24. Lu TW, O'Connor JJ. Bone position estimation from skin marker co-ordinates using global optimisation with joint constraints. *J Biomech*. 1999;32(2):129-134. doi:10.1016/S0021-9290(98)00158-4
25. Baker R. Pelvic angles: A mathematically rigorous definition which is consistent with a conventional clinical understanding of the terms. *Gait Posture*. 2001;13(1):1-6. doi:10.1016/S0966-6362(00)00083-7
26. Winter DA. *The Biomechanics and Motor Control of Human Movement*. 2nd ed. New York.: Wiley; 1990.
27. Li L, Van Den Bogert ECH, Caldwell GE, Van Emmerik REA, Hamill J. Coordination patterns of walking and running at similar speed and stride frequency. *Hum Mov Sci*. 1999;18(1):67-85. doi:10.1016/S0167-9457(98)00034-7
28. Galgon AK, Shewokis PA. Using mean absolute relative phase, deviation phase and

point-estimation relative phase to measure postural coordination in a serial reaching task. *J Sport Sci Med*. 2016;15(1):131-141.

29. Decker L, Houser JJ, Noble JM, Karst GM, Stergiou N. The effects of shoe traction and obstacle height on lower extremity coordination dynamics during walking. *Appl Ergon*. 2009;40(5):895-903. doi:10.1016/j.apergo.2008.12.005
30. Stergiou N, Jensen JL, Bates BT, Scholten SD, Tzetzis G. A dynamical systems investigation of lower extremity coordination during running over obstacles. *Clin Biomech (Bristol, Avon)*. 2001;16(3):213-221. doi:10.1016/s0268-0033(00)00090-5
31. Bernstein NA. *The Co-Regulation of Movements*. Oxford: Pergamon Press; 1967.
32. Broderick MP, Newell KM. Coordination patterns in ball bouncing as a function of skill. *J Mot Behav*. 1999;31(2):165-188. doi:10.1080/00222899909600986
33. Davids K, Araujo D, Hristovski R, Passos P, Chow JY. Ecological dynamics and motor learning design in sport. In: Hodges N.J., Williams AM, ed. *Skill Acquisition in Sport: Research, Theory & Practice*. 2nd ed. New York (USA): Routledge; 2012:112-130.
34. Kiely J. Periodization Paradigms in the 21st Century: Evidence-Led or Tradition-Driven? *Int J Sports Physiol Perform*. 2012;7(3):242-250. doi:10.1123/ijspp.7.3.242
35. Woods CT, McKeown I, Rothwell M, Araújo D, Robertson S, Davids K. Sport Practitioners as Sport Ecology Designers: How Ecological Dynamics Has Progressively Changed Perceptions of Skill "Acquisition" in the Sporting Habitat. *Front Psychol*. 2020;11:654. doi:10.3389/fpsyg.2020.00654
36. Kim J-W, Kwon M-S, Yenuga SS, Kwon Y-H. The effects of target distance on pivot hip, trunk, pelvis, and kicking leg kinematics in Taekwondo roundhouse kicks. *Sport Biomech*. 2010;9(2):98-114. doi:10.1080/14763141003799459
37. Preuschl E, Hassmann M, Baca A. A kinematic analysis of the jumping front-leg axe-kick in taekwondo. *J Sport Sci Med*. 2016;15(1):92-101.

Table Captions

Table 1 Marker definition and tracking set-up.

Table 2 Maximum centre of mass segment velocities of kicking legs ($m.s^{-1}$). Mean ± SEM values.

Figure Captions

Figure 1 — Arrangement of the target against which the taekwondo players performed the roundhouse kick. **(a-b)** Half-sphere concrete base that held the post and kicking bag. **(c)** Instruction panel on A3-size screen. **(d)** Aluminium plate with triaxial accelerometer attached. **(e)** Secure mounting of aluminium plate inside kicking bag via four self-tap screws **(f)**.

Figure 2 — Roundhouse kick instances. Toe-off **(a**, TO**)**, Maximum Knee Flexion **(b**, MF**)** and Impact **(c**, IM**)**.

Figure 3 — Piecewise linear regression. An elite knee-hip CRP curve is represented by a grey solid line, linear fits by dashed lines and knots by black dots. The magnified window shows detail of the third phase and the fifth and sixth knots and the general piecewise linear regression equation. y is the observed variable, β_0 is the y intercept, β_1 is the gradient, x is time and ε is an error term.

Figure 4 — Continuous relative phase curves for periods TO-MF and MF-IM. Non-elite and elite player data are represented in **(a)** and **(c)**, and **(b)** and **(d)** respectively; knee-hip and ankle-knee joint couplings in **(a)** and **(b)**, and **(c)** and **(d)** respectively. The solid line represents the mean of CRP curves, and the grey area represents mean ± SEM (n = 27).

Figure 5 — Piecewise linear regression gradients for elite (solid line) and non-elite (dashed line) CRP curves, varying by taekwondo group, kicking period and joint relation. * indicates significant differences between elite and non-elite groups as a main effect.

Figure 6 — Mean absolute relative phase values **(a)** and deviation phase values **(b)** for CRP curves of elite (solid line) and non-elite (dashed line) taekwondo players. Error bars represent ± SEM with respect to the mean. n = 27 for all data points.

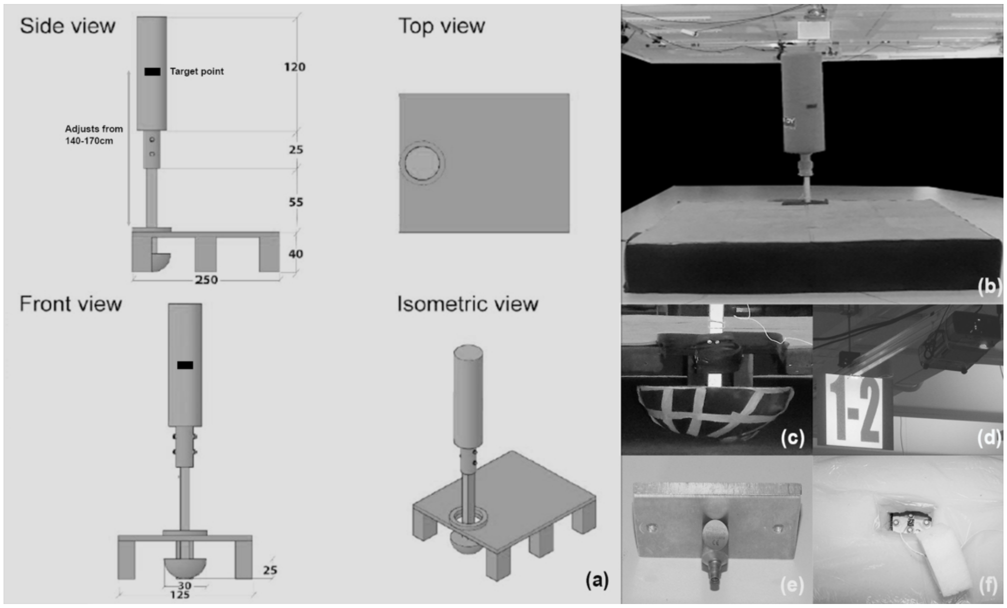

Figure 1 — Arrangement of the target against which the TKD players performed the roundhouse kick. (a-b) Half-sphere concrete base that held the post and kicking bag. (c) Instruction panel on A3-size screen. (d) Aluminium plate with triaxial accelerometer attached. (e) Secure mounting of aluminium plate inside kicking bag via four self-tap screws (f).

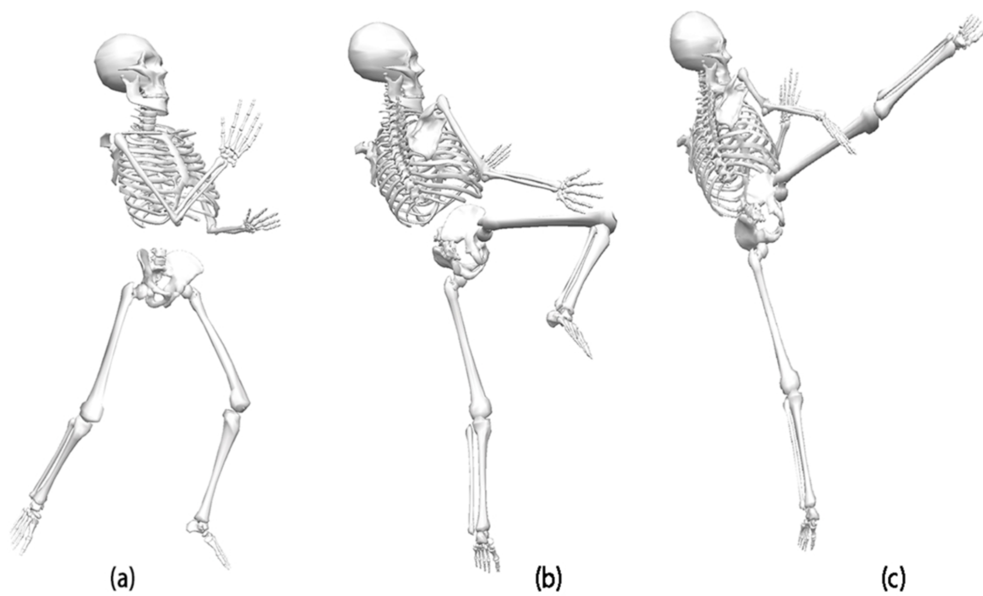

Figure 2 — Roundhouse kick instances. Toe-off (a, TO), Maximum Knee Flexion (b, MF) and Impact (c, IM).

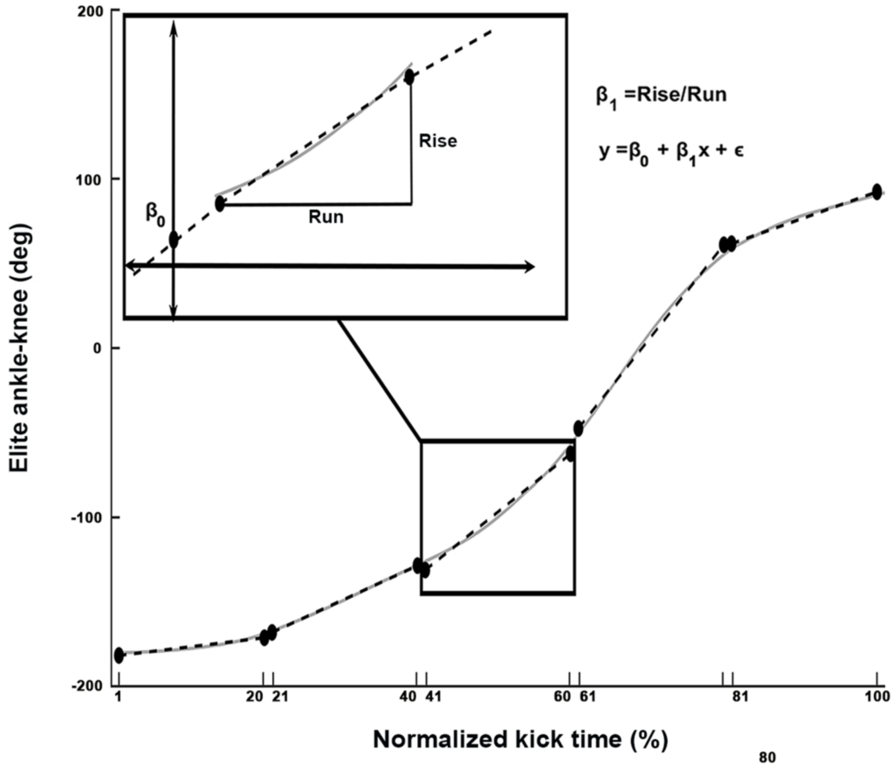

Figure 3 — Piecewise linear regression. An elite knee-hip CRP curve is represented by a grey solid line, linear fits by dashed lines and knots by black dots. The magnified window shows detail of the third phase and the fifth and sixth knots and the general piecewise linear regression equation. y is the observed variable, β_0 is the y intercept, β_1 is the gradient, x is time and ε is an error term.

120x99mm (600 x 600 DPI)

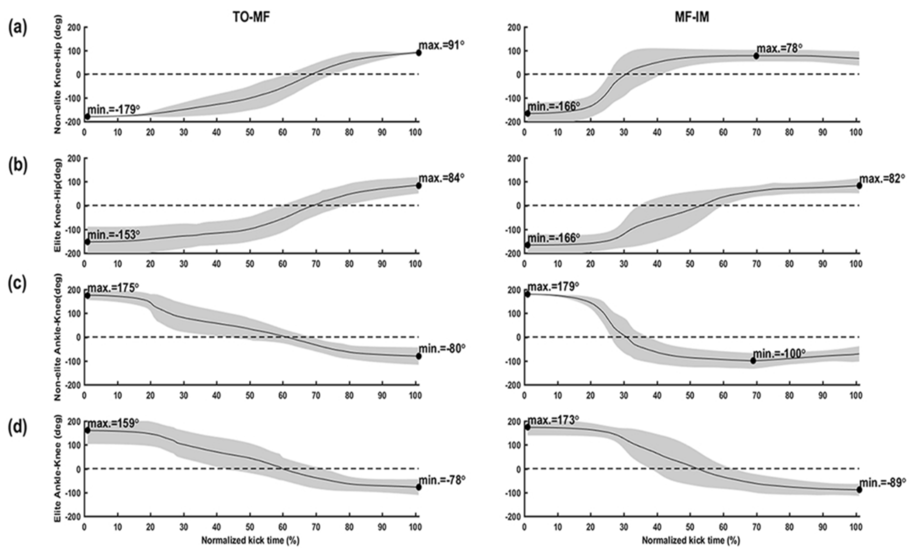

Figure 4 — Continuous relative phase curves for periods TO-MF and MF-IM. Non-elite and elite player data are represented in (a) and (c), and (b) and (d) respectively; knee-hip and ankle-knee joint couplings in (a) and (b), and (c) and (d) respectively. The solid line represents the mean of CRP curves, and the grey area represents mean ± SEM (n = 27).

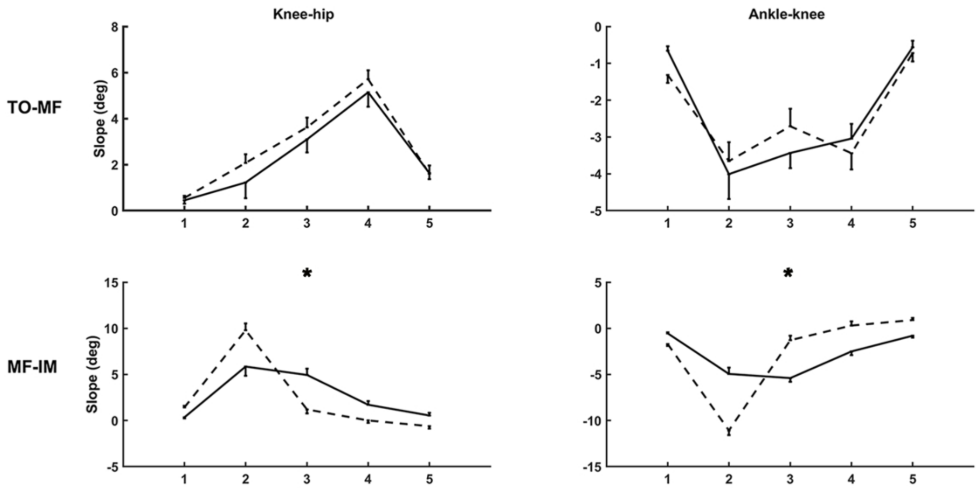

Figure 5 — Piecewise linear regression gradients for elite (solid line) and non-elite (dashed line) CRP curves, varying by TKD group, kicking period and joint relation. * indicates significant differences between elite and non-elite groups as a main effect.

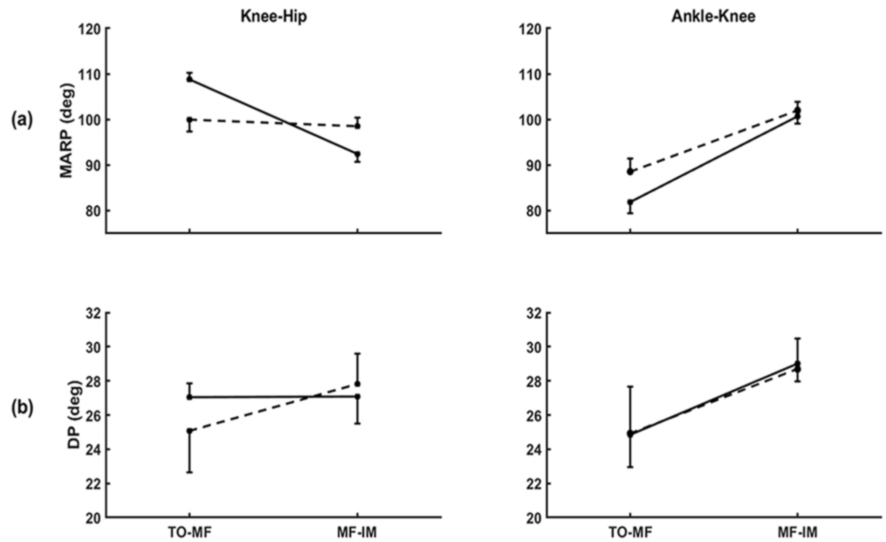

Figure 6 — Mean absolute relative phase values (a) and deviation phase values (b) for CRP curves of elite (solid line) and non-elite (dashed line) TKD players. Error bars represent ± SEM with respect to the mean. n = 27 for all data points.

Table 1

Segment	Labels	Numbers	Definition	Tracking	Description
Pelvis	ASIS	2	✓	✓	Anterior Superior Iliac Spine
	PSIS	2	✓	✓	Posterior Superior Iliac Spine
Thigh	LEC	2	✓		Lateral Epicondyle of the Femur
	MEC	2	✓		Medial Epicondyle of the Femur
	Rigid cluster of four markers were firmly attached anteriorly and proximally with Fabrifoam wrap				
	THI1	2		✓	Thigh 1
	THI2	2		✓	Thigh 2
	THI3	2		✓	Thigh 3
	THI4	2		✓	Thigh 4
Shank	LMAL	2	✓		Lateral Malleolus
	MMAL	2	✓		Medial Malleolus
	Rigid cluster of four markers were firmly attached laterally and distally with Fabrifoam wrap				
	SHK1	2		✓	Shank 1
	SHK2	2		✓	Shank 2
	SHK3	2		✓	Shank 3
	SHK4	2		✓	Shank 4
Foot	MET1D	2	✓		First Metatarsal
	MET5D	2	✓		Fifth Metatarsal
	CAL	2	✓		Calcaneus
	Rigid cluster of three markers were firmly attached on lateral and medial side with adapted ankle support				
	FOT1	2		✓	Foot 1
	FOT2	2		✓	Foot 2
	FOT3	2		✓	Foot 3
Individual marker		18	18	4	
Cluster marker		22		22	
Total		40	18	26	

Table 2

	TO-MF		*MF-IM*	
	Non-elite	Elite	Non-elite	Elite
Pelvis	0.9 (± 0.1)	1.2 (± 0.3)	1.9 (± 0.1)	2.3 (± 0.1)
Thigh	1.2 (± 0.1)	2.2 (± 1.1)	2.3 (± 0.9)	2.7 (± 0.1)
Shank	**5.3 (± 0.6)***	**6.9 (± 0.3)***	**6.3 (± 0.4)***	**7.6 (± 0.3)***
Foot	8.8 (± 0.4)	9.5 (± 0.3)	**11.3 (± 0.8)***	**13.6 (± 0.6)***

* indicates a significant difference between elite and non-elite.