Heliyon 9 (2023) e20843

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Biomechanics research on laterality effect between dominant and non-dominant during double roundhouse kick in the competitive taekwondo

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A R T I C L E I N F O

Keywords:
Competitive taekwondo
Double roundhouse kick
Dominant side
Non-dominant side
Symmetry index

A B S T R A C T

Background: The Double Roundhouse Kick (DRK) is one of the major scoring tools and athletes employ the leg of the dominant side (DS) or the non-dominant side (NS) for always attacking in an alternating state. The purpose is to examine the discrepancies in the biomechanical characteristics of the DS and NS of the leg of the DRK skills of sub-elite taekwondo athletes.

Methods: Using the Vicon, Kistler, and Daedo brand Electronic Body Protector (EBP), collection of the DRK data (attack time, joint angle, joint angular velocity, joint moment, ground reaction force, etc.) of 12 sub-elite taekwondo athletes (19.6 ± 2.0 yr, 180 ± 7.3 cm, 70 ± 9.8 kg) with the DS leg and NS leg. The measured data analyses via Visual3D, and statistical methods using nonparametric tests paired with samples based on the Wilcoxon signed-rank test (The significance level is set as significant for $P < 0.05$, and very significant for $P < 0.01$).

Results: (i) There is no statistically significant discrepancy between the DS and NS at the time of hit ($P > 0.05$) and shift of the center of gravity ($P > 0.05$). (ii) Attacking leg (AL): the maximum knee flexion angle (Knee-MFA) ($P < 0.05$) and the peak linear velocity of attack of the foot in the vertical hitting direction ($P < 0.01$) on the DS was greater than that on the NS during the first hit phase (P1). (iii) Supporting leg (SL): the peak hip extension moment ($P < 0.05$) on the DS was reported to be higher than that of the NS during the second hit phase (P2). (iv) Symmetry Index (SI): In the P1, the vertical ground reaction force (vGRF) of the SL leads to SI = 10.19 %, and in the P2, the vGRF of the SL results in SI = 18.48 %.

Conclusions: The DRK requires more and more symmetry between the DS and NS. The Knee-MFA of the AL and the line of attack speed of the foot in the vertical striking direction of the SL exhibited significant discrepancies. The DS has higher striking speed, athletes need to improve the striking speed of the NS leg in training, achieving more scoring opportunities in the game. Both the DS and NS revealed strong symmetry in the peak SI of the ground reaction force of the SL stirrup; however, weak symmetry was attained in the peak SI of the vGRF of the SL landing cushion.

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https://doi.org/10.1016/j.heliyon.2023.e20843
Received 30 May 2023; Received in revised form 6 October 2023; Accepted 9 October 2023
Available online 12 October 2023

1. Introduction

The World Taekwondo (WT) introduced the use of EBPs in competitive taekwondo at the 2008 Beijing Olympics in the Olympic Games to make competitions more spectator-friendly and fair [1]. The impact magnitude of a kick hitting the EBP must exceed a specific threshold for each athlete's weight category in new taekwondo competitions to score instead of making a loud kicking sound to score. The utilization of EBPs has placed higher demands on further enhancing the strength and accuracy of the athlete's strikes; further, sharp judgment, quick strikes, and precise strikes have become key factors in winning taekwondo competitions [2].

So, competitive taekwondo, as a combat sport with direct physical contact and more intense confrontation, requires athletes to perform kicks and strikes with optimal speed and appropriate force during the competition [1,2]. The DRK action based on the horizontal kick action is the first in terms of speed and frequency of consecutive strikes, with technical characteristics such as technical characteristics of the strong concealment, high striking power, fast striking speed, surprise, and fast articulation. The match statistics data has revealed that the DRK is one of the major scoring tools, and the DRK is second only to the horizontal kick technique in terms of the number of times it is employed in the match [3,4], but the success rate exceeds that of the horizontal kick, particularly in the lightweight matches where the DRK is the highest technical score [5].

The striking speed and the power of the attacking leg in taekwondo are crucial factors affecting athletic performance [6], while the angular velocity variation of the ankle joint of the attacking leg has a noticeable impact on the power and speed of the strike [7], and the knee joint extension and the hip joint movement are the crucial key and basis for the ankle joint to achieve maximum speed [8]. The angle and speed of the hip abduction angle of the supporting leg also directly influence the movement speed of the attacking leg, [9] and the sensing characteristics of the EBP suggest that the effective score is related to the sensing threshold of the EBP [10]. Hence, the speed, strength, and precision of the offense in competitive taekwondo competition in the presence of the tactical guidelines of offense-oriented are directly related to the athletes' motion characteristics of the lower limb hip, knee, and ankle joints [6–9,11–13].

Furthermore, in addition to the direct effect of sports technical movement characteristics on athletic performance, athletes could experience structural and functional asymmetries between the left and right limbs due to long-term specialized training [14,15]. The existence of asymmetry in muscle strength in the hip, knee, and ankle joints of both limbs of athletes as a potential influencing factor constrains or limits athletic performance [16–22]. The variability in athletic performance due to left-right asymmetry in athletes is actually a problem of lateral limb laterality. The lateralization of the limb is commonly influenced by the interaction of genetic and environmental factors, but the formation and strengthening of lateralization are most affected by the late environment [19]. Explorations of lower limb kicking skills have displayed that athletes customarily exploit the unilateral leg, which remarkably disrupts the strength balance between the synergistic and antagonistic muscle groups of the extremities and reinforces the laterality of the lower limb, which the vast majority of athletics require athletes to reduce such an influence [23,24].

Competitive taekwondo is a sport that focuses on continuous kicking and striking the opponent, and the DRK always has the AL and SL in an alternating state. The major appearance of the attack is to break the opponent's defense and deliver a precise and powerful kick [25]. In training, coaches often require athletes to exploit their dominant leg as the main attack leg for intensive training, and the muscular strength of body joints develops in the direction of irregularity and asymmetry. The increasing asymmetry of the left and right-side hip, knee, and ankle joint activities of taekwondo athletes cause the limbs to be divided into DS and NS [26].

The DRK is based on the roundhouse kick action of two consecutive striking actions on the left and right sides and is a technical action that fully utilizes the rotation of one's hips and trunk in a supported state and exploits the swing of the three joints of the hips, knees, and ankles to attack from the side [27]. Asymmetries in the right and left side of the athlete's hip, knee, and ankle could also directly affect athletic performance [27]; additionally, athletes who want to enhance their athletic performance must reduce the complement of the DS to the NS [28].

The majority of the literature about the DRK today concerns the technical and tactical shifts necessitated by the new rules [29], the biomechanical characteristics of individual techniques [30], and the impact of sports training on the kick itself [31,32], Few investigations have been devoted to the effect of lower limb asymmetry on the athletic performance in taekwondo athletes. To further clarify the characteristics of the DRK, which are easy to initiate, high striking power, and fast striking frequency, this exploration collected kinematic and kinetic data of sub-elite taekwondo athletes' DRK in the presence of the judgment score of striking EBP. Inverse kinematic and kinetic calculations were performed by employing Visual3D motion biomechanics simulation software. One of the main objectives was to perform a comparative analysis of lower extremity kinematic and kinetic characteristics of the DS and NS to explore the discrepancies in the sports biomechanical characteristics of the DS and NS of the lower limbs in the DRK technical movements of sub-elite taekwondo athletes under the impact of EBP determination scores. Such explorations will reveal some biomechanical aspects of the joints on the DS and NSs of the lower extremity in the DRK and are aimed to provide theoretical support for the scientific training and efficient competition of the DRK.

2. Materials and methods

2.1. Participants

GPower 3.1.9.7 is utilized to evaluate the predicted sample size. A correlation analysis using a larger effect size of $d = 0.7$ required at least 11 participants at a significance level of $\alpha = 0.05$ and a statistical power (1-β) of 80 % [33,34]. The participants of this study include 12 male athletes from the taekwondo specialized training team (19.6 $\pm$ 2.0 years, 180 $\pm$ 7.3 cm, 70 $\pm$ 9.8 kg, and the average training history is 3.8 $\pm$ 2.0 years). All participants are at the national first level or above. All participants trained for more than three consecutive years, five days a week, 3 h per day. All participants did not undergo high-intensity training within 24 h before the test and have reported no injuries in the past six months. Before the experiment, all participants understand the experimental process. This study passed the ethical review of Wuhan Sports University (NO. 2020048).

2.2. Definition of the dominant side

Due to the different intensity of training and the discrepancy characteristics of lower limb function, taekwondo athletes' lower limbs form a dominant side and non-dominant side on the left and right sides, and the leg that is often employed to attack the opponent is called the dominant side leg. In this investigation, two participants had the left leg on the dominant side, and ten participants had the right leg on the dominant side.

2.3. Measurements and procedures

The markers pasting scheme refers to the Vicon's own Plug-In Gait 39 points full body model. Based on the Vicon's own Plug-In Gait 39 points full body model, according to the characteristics of the DRK, which essentially relies on the lower limbs for attacking, the marker points of the upper limbs have been removed, and tracking points have been added to the hip, thighs, calves, and feet.

The participants were asked about their health and asked to sign an informed consent form. They were also told how the experiment would work and what precautions to take. Before starting the experiment, all participants were asked to warm up for 5 min on a treadmill at a speed of 6.5 km/h [35], and the participants performed stretching and predicted movement exercises. Before the formal kick strike, the participant was asked to stand on the left and right sides of the feet on two independent force table plates for static calibration of Vicon data. A plastic dummy wearing EBP was placed in front of the participant, the participants were given permission to swiftly strike the dummy and the location of the target dummy, as well as to change the dummy's height to correspond with the standard height of the electronic guard at the subject's striking. As soon as the participants is ready, the participant completed the first (1st) and second (2nd) single-strike patterns of the DRK with the DS and NS initiation, respectively.

The first single-hit pattern initiated on the DS is called 1st-DS, the second single-hit pattern initiated on the DS is called 2nd-NS (actually non-dominant leg strike), and the first hit single hit pattern initiated on the NS is called 1st-NS, and the second hit single hit pattern initiated on the NS is called 2nd-DS (actually dominant leg strike). After each action, the same coach determined whether or not the participant's performance met the technical requirements for a DRK.

2.4. Instruments and evaluation index

2.4.1. Instruments

The kinematic parameters were acquired via a Vicon 3D motion capture system (T40, Vicon, UK, 200 Hz). The ground reaction force of the SL was collected via a Kistler force plate (9260AA6, Switzerland, 1000 Hz). The WT-approved Daedo EBP (EBP-TK STRIKE, Daedo International, Spain) is employed.

2.4.2. Data processing

The Vicon system was synchronized with the Kistler system via a digital signal converter to collect kinematic and kinetic data. In 3D motion capture, there are many missing marker points. Vicon Nexus 2.9.1 matches the marker points acquired under static conditions and connects them with the bone marker points in the Vicon model. At the same time, the missing marker points subjected to the dynamics state were connected by complementary points, and finally, the data were exported to C3D format, and then the C3D data were imported into Visual3D (C-Motion, Inc., Germantown, MD, USA), the kinematic(kinetic) data were processed with low-pass 10 (25) Hz filtering.

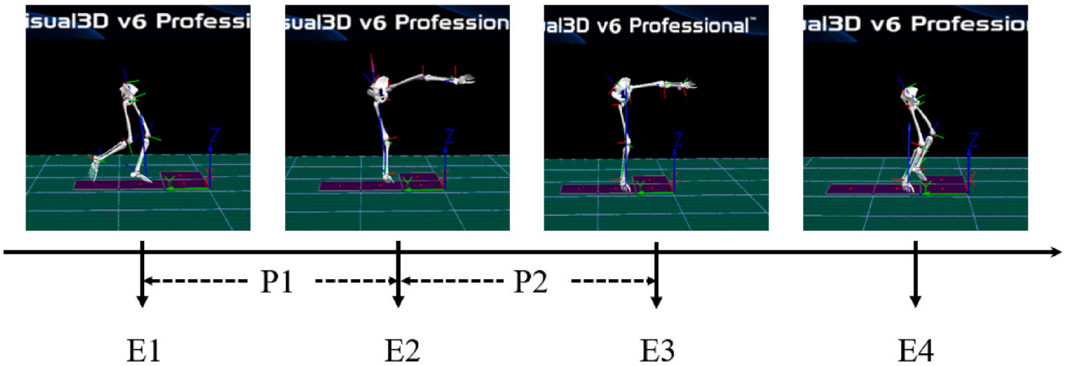

Fig. 1. Event.

2.4.3. Event division

To clearly analyze the athletic biomechanical characteristics of the DRK, the entire action could be divided into specific moments [36]. Preparation moment (E1): the moment when the first striking leg leaves the ground. First hit moment (E2): the moment of the first hit. Second hit moment (E3): the moment of the second hit. Recovery moment (E4): the moment of touching the ground after the second striking leg has finished striking. P1: the moment of the E1 to E2. P2: the moment of the E2 to E3 (see Fig. 1).

2.4.4. Evaluation index

For the DRK assessment, the action completion time of two strikes, the Body center of gravity (COG), lower limb joint range of motion (ROM) and speed, vGRF, the moment during the striking process and the SI were considered.

(1) Completion time: the first hit time, the second hit time, and the total hit time is the completion time from E1 to E2, E2 to E3, and E1 to E3, respectively [36].
(2) ROM: the maximum range of angles and amplitudes (°) of hip and knee flexion and extension. Defined as a positive direction for hip flexion and knee extension; defined as a negative direction for hip abduction and knee flexion [19,20].
(4) Lower limb angular velocity of motion (VOM): the maximum angular velocity (rad/s) of hip, knee, and ankle joints. Define the angular velocity of hip flexion and knee extension as a positive direction; define the angular velocity of hip abduction and knee flexion as a negative direction [35,36].
(5) Kinetics: normalized maximum vGRF after weight, i.e., GRF (BW), maximum hip-knee-ankle moment (N-m/kg), and maximum power (W/kg) [37].
(6) SI: the maximum ground reaction force (GRFmax) of the SL during the support period is chosen as a major basis to evaluate the symmetry of the lower limbs on both sides [19]. The equation is shown in (1):

$$\mathrm{SI} = \left| \frac{DS - NS}{\frac{1}{2}(DS + NS)} \right| \times 100\% \tag{1}$$

where SI = 0 indicates symmetry on both sides, SI $\leq$ 10 % represents strong symmetry on both sides with a strongly symmetrical area, and SI>10 % is associated with the fact that the larger the value, the lower the symmetry on both sides, representing a weakly symmetrical area [19,35,38].

2.5. Data analysis

Statistical software was utilized for analysis based on Origin 2022. The kinematic and kinetic index parameters solved for participants' DS and NS DRK were expressed as the mean ± standard deviation (SD). Data were tested for normal distribution, with some data excluded from normality employing the nonparametric tests paired sample. Wilcoxon signed-rank test methodology was utilized to evaluate the discrepancies between the DS and NS of the leg; further, the significance level is set as significant for $P < 0.05$, and very significant for $P < 0.01$.

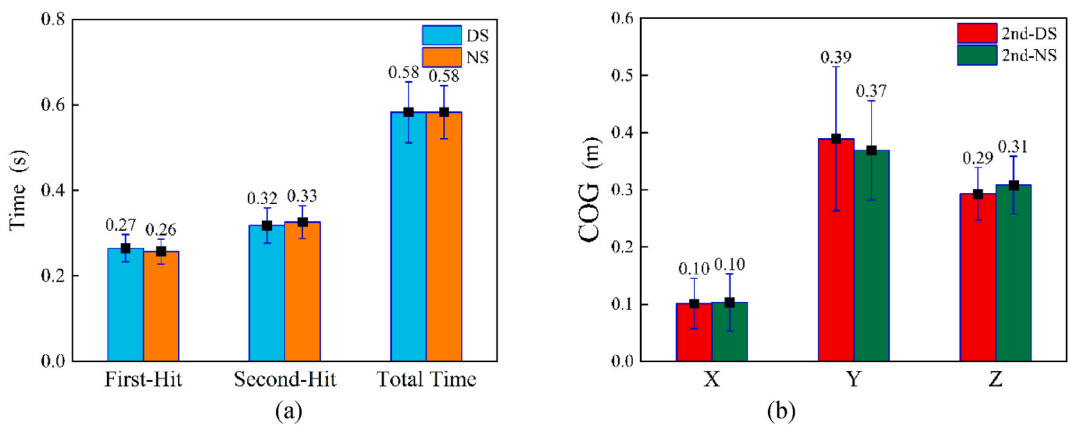

Fig. 2. Effects of the attack time and COG on the DRK: (a) attack time, (b) COG shift ((*) significant discrepancy $P < 0.05$, (**) very significant discrepancy, $P < 0.01$).

3. Results

3.1. Action completion time and COG movement characteristics

Fig. 2(a) demonstrates the discrepancies between the dominant and non-dominant sides in terms of various attack time intervals, including first hit time, second hit time, and total hit time. The obtained results indicate that there is no statistically significant discrepancy (P>0.05). In the present investigation, the COG shift in the P2 is chosen. Fig. 2(b) presents the discrepancies between the dominant and non-dominant sides in the left and right (X-axis), front and back (Y-axis), and up and down (Z-axis) directions of the attack. The depicted results reveal that there is no statistically significant discrepancy (P>0.05).

3.2. Kinematic and kinetic characteristics of the hip joint

As illustrated in Fig. 3(a), in the sagittal plane during the P1, in the maximum angle of the hip flexion (Hip-MFA), flexion range of motion (Hip-FOM), and maximum flexion angular velocity (Hip-MFAV) of the attacking leg, the discrepancies in the maximum flexion moment (Hip-MFM) and the maximum extension moment (Hip-MEM) of the supporting leg, there is no statistically significant discrepancy (P>0.05) when comparing the dominant side with the non-dominant side.

During the P2, in the maximum angle of flexion (Hip-MFA), flexion range of motion (Hip-FOM), and maximum flexion angular velocity (Hip-MFAV) of the attacking leg, the maximum flexion moment (Hip-MFM) of the supporting leg, there is no statistically significant discrepancy (P>0.05) between the dominant and non-dominant sides. The maximum support leg extension moment (Hip-MEM) on the dominant side was greater than that on the non-dominant side (P < 0.05).

In the frontal plane, Fig. 3(b) shows the discrepancies in maximum outward angle (Hip-MOA), outward range of motion (Hip-OROM), and maximum abduction angular velocity (Hip-MOAV) of the hip joint of the attacking leg in the P1 and P2, the maximum outward moment (Hip-MOM) and the maximum inward moment (Hip-MIM) of the supporting leg, the demonstrated results indicated that there is no statistically significant discrepancy between the dominant and non-dominant sides (P>0.05).

3.3. Knee joint kinematic and kinetic characteristics

As demonstrated in Fig. 4(a), in the sagittal plane during the P1, the maximum angle of knee flexion of the attacking leg (Knee-MFA) on the dominant side was greater than that on the non-dominant side (P < 0.05). Further, the discrepancy between the maximum flexion angular velocity (Knee-MFAV), the maximum flexion moment of the supporting leg (Knee-MFM) on the dominant side and that of the non-dominant side indicated that there is no statistically significant discrepancy (P>0.05). Concerning the P2, the discrepancies in the maximum angle of knee flexion (Knee -MFA) and the maximum flexion angular velocity (Knee-MFAV) of the attacking leg, the maximum flexion moment (Knee-MFM) of the supporting leg revealed that there is no statistically significant discrepancy (P>0.05) through comparing the dominant side with the non-dominant side.

According to the plotted results in Fig. 4(b) for the sagittal plane during the phases P1 and P2, in the extension range of motion (Knee-EROM) and the maximum extension angular velocity (Knee-MEAV) of the knee joint of the attacking leg, the maximum extension moment (Knee-MEM) of the supporting leg, no statistically significant discrepancy (P>0.05) between the dominant side and the non-dominant side was observed.

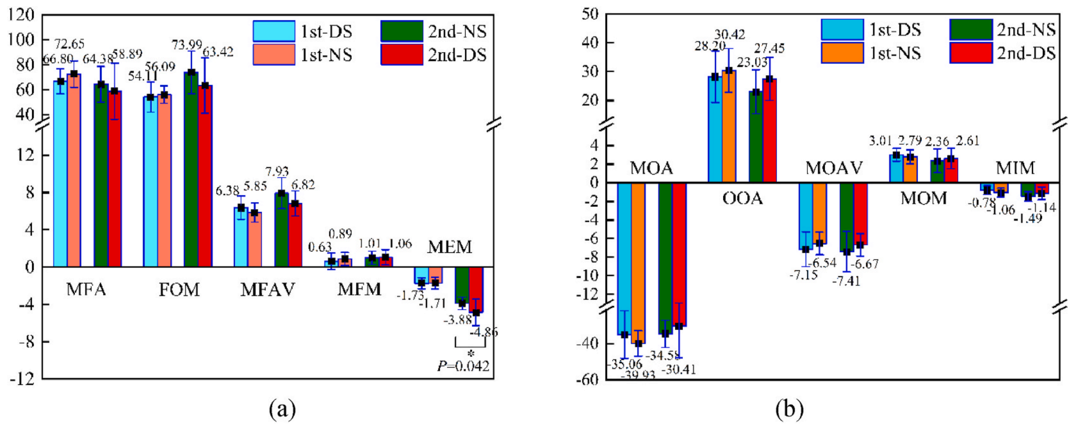

Fig. 3. Biomechanical characteristics of the hip joint on the DRK: (a) hip flexion/extension, (b) hip outward/inward (note: maximum flexion angle (MFA); flexion range of motion (FROM); maximum flexion angular velocity (MFAV); maximum flexion moment (MFM); maximum extension moment (MEM); maximum outward angle (MOA); outward range of motion (OROM); maximum outward angular velocity (MOAV); maximum outward moment (MOM); maximum inward moment (MIM); (*) significant discrepancy, P < 0.05; (**) very significant discrepancy, P < 0.01).

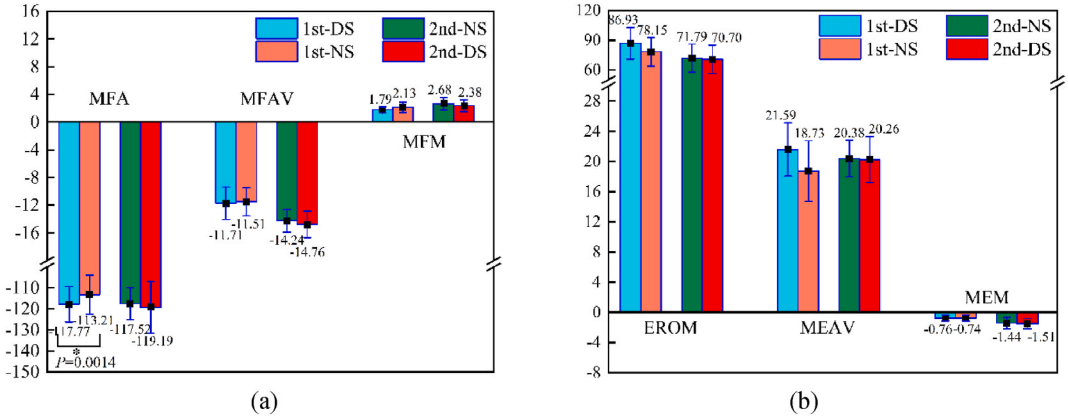

Fig. 4. Biomechanical characteristics of the knee joint on the DRK: (a) knee flexion, (b) knee extension (maximum flexion angle (MFA); maximum flexion angular velocity (MFAV); maximum flexion moment (MFM); extension range of motion (EROM); maximum extension angular velocity (MEAV); maximum extension moment (MEM); (*) significant discrepancy $P<0.05$, (**) very significant discrepancy, $P<0.01$).

3.4. Kinematic and kinetic characteristics of foot and ankle joints

Fig. 5(a) displays the discrepancies between the maximum dorsiflexion moment (Ankle-MDM) around the frontal axis, maximum external flip moment (Ankle-MEFM) around the sagittal axis, and maximum internal rotation moment (Ankle-MIRM) around the vertical axis of the supported leg ankle joint in the P2. The demonstrated results revealed that no statistically significant discrepancy ($P>0.05$) is detectable when comparing the dominant side with the non-dominant side. The kinetic characteristics of the ankle joint of the support leg were not examined during the P1 due to the limitations of the Kistler force plate position and the target dummy position.

The depicted results for phase P1 in Fig. 5(b) indicated that the maximum foot velocity of the attacking leg on the X-axis on the dominant side was greater than that on the non-dominant side ($P<0.01$). Further, the discrepancy between the dominant and non-dominant sides of the maximum foot velocity of the attacking leg on the Y-axis and Z-axis indicated that there is no statistically significant discrepancy ($P>0.05$). Concerning the maximum foot velocity of the attacking leg on the X-axis, Y-axis, and Z-axis, no statistically significant discrepancy between the dominant side and the non-dominant side ($P>0.05$), in phase P2 is detectable.

3.5. Vertical ground reaction force and symmetry index

As illustrated in Fig. 6(a), in the direction of the vertical axis (Z-axis) of the lab coordinate system, the GRF_{max} of the support leg in phases P1 and P2, there is no statistically significant discrepancy ($P>0.05$) between the dominant and non-dominant sides. Fig. 6(b) provides the maximum vertical ground reaction force symmetry index ((Eq. (1))) in phase P1. The demonstrated results indicate that the maximum ground reaction force symmetry index in the vertical direction (SI-GRF-1st) of the support leg was 10.19 % ± 4.8≈10 %. Additionally, in phase P2, the maximum ground reaction force symmetry index in the vertical direction (SI-GRF-2nd) of the support leg

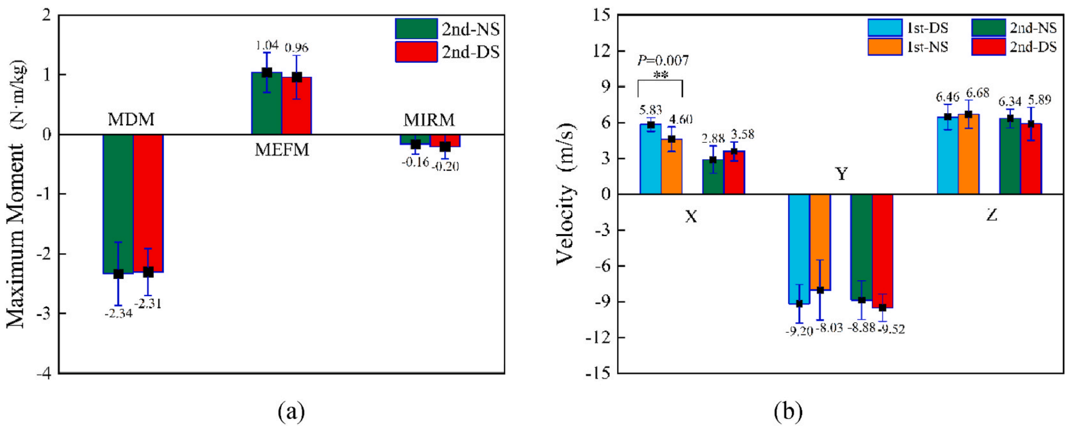

Fig. 5. Biomechanical characteristics of the ankle joint on the DRK: (a) ankle joint moment, (b) striking speed (maximum ankle dorsiflexion moment (Ankle-MDM); maximum external flip moment (MEFM); maximum internal rotation moment (MIRM); (*) significant discrepancy, $P<0.05$; (**) very significant discrepancy $P<0.01$).

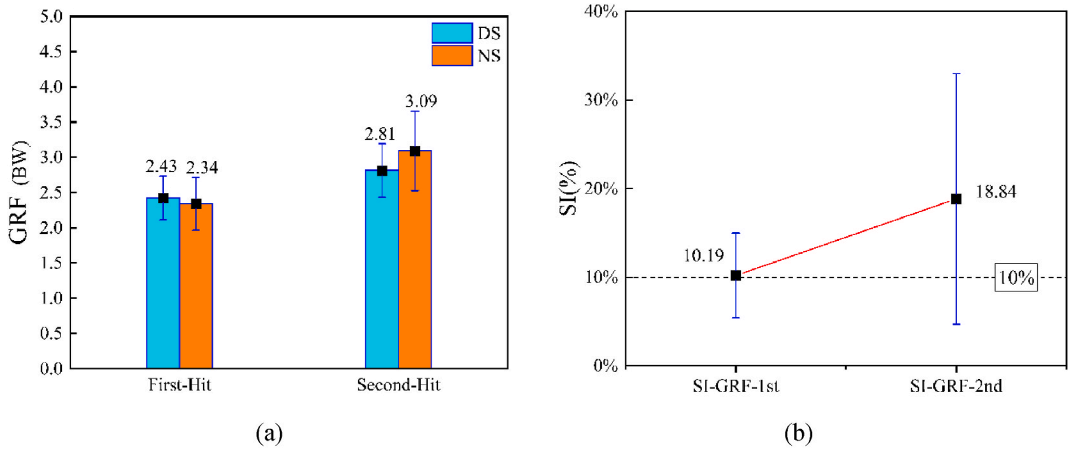

Fig. 6. Peak vertical GRF and SI characteristics: (a) vertical ground reaction force, (b) symmetry index ((*) significant discrepancy, $P < 0.05$; (**) very significant discrepancy, $P < 0.01$).

was estimated to be 18.84 % ± 14.2 >10 %.

4. Discussion

4.1. Completion time and COG offset

The DRK technique of taekwondo is classified according to the kinematic characteristics of taekwondo kicks as swing kicks and attacking kicks, where the AL commonly employs the maximum swing to enhance the speed of the foot at impact [39], based on left and right leg roundhouse kick movements with high speed and continuity. Further, in Wasik's exploration, it was emphasized that the strike time of a single cross-kick would be 0.25 s [40], which is similar to the results of the present study. The depicted results in Fig. 2 (a) indicated that the DRK did not exhibit statistical discrepancies in the first, second, and total hit time, and the values were very similar in magnitude. It implies that the discrepancies between the DS and NS of the DRK in terms of hitting time on both sides were small.

In another study, it was pointed out that the COG offset in the X-axis could signify the stability of the body during movement [41]. In general, the smaller movement of the COG in the left and right directions relative to the hitting target, the better the stability is, and maintaining the body balance provides the conditions for the AL to play the maximum hitting effect. In P1, the participant's body balance was well controlled, while in the P2 after taking off, the participant's COG began to lose balance, and the stability of the body after completing the second hit would be crucial for the later attack and defense; hence, the COG shift data in the P2 was selected for the laterality analysis. In the P2, no statistically significant discrepancy between the DS and NS in the offset of the COG in the left and right (X-axis), front and back (Y-axis), and up and down (Z-axis) of the hitting target during the DRK action was observed. It indicates that the discrepancies between the DS and NS for the stability of the COG when hitting the target with the DRK were trivial.

4.2. Lower limb joint angle and ROM

The DRK is essentially based on the roundhouse kick action of the left and right sides to perform two successive rapid striking actions of the roundhouse kick actions in the process of torso rotation twice. The first rotation is to provide space for the action of the attacking leg, and the second rotation for the attacking leg is responsible for the striking speed. After the attacking leg leaves the ground, the lower leg is folded towards the thigh: the hip joint is abducted, the knee joint is flexed, and at the moment of striking: the knee joint is quickly extended and the hip joint is flexed. The DRK is characterized by the full use of its own hip joint, the rotation of the trunk, and the sequential completion of the striking action according to the sequence of movement of the hip, knee, and ankle joints [27].

In swing kicks, the striking speed is one of the competition-winning factors and is directly related to the muscle force generated by the quadriceps during knee extension, and the muscle force magnitude mostly depends on the knee flexion-extension angle [42]. In order to better reflect the kinematic characteristics of the attack phase of the DRK, the kinematics of the knee and hip joints were selected for the present scrutiny. More accurately, the peak kinematic parameters of the knee and hip joints were chosen for laterality analysis. Through comparing the biomechanical parameters of the hip and knee joints on the DS and NS in Fig. 3(a), 4(a) and 5(b), these three plotted results indicate that the main factor affecting the strike speed during the DRK action when striking the target is the flexion angle of the knee joint [43]. The hip and knee joints of the attacking leg no exhibited noticeable discrepancies between the dominant side and the non-dominant side in other indexes; however. The data provided in Figs. 5 and 6 also revealed that the hip and knee joints of the AL do not exhibit noticeable discrepancies between the DS and NS in other indexes; however, the hip and knee joints of the DS had a greater range of motion, reflecting the better motion performance of the DS during the striking process.

4.3. Lower limb joint angular velocity and foot velocity

The DRK action requires fast, powerful, and accurate strikes, and the maximum speed is obtained at the end of the AL through the interplay of all joints and segments of the whole body [42]. The DRK-whipping action is basically the rotation of the human torso and the corresponding segments of the lower limbs around their respective axes. The effectiveness of the striking is determined by various contraction forms and characteristics of the muscle groups involved in the action based on various action stages and sequences [27].

The angular velocity of the joint chiefly describes how fast the segments at the ends of the joint rotate around the joint, and the magnitude of the completion speed is influenced by the acceleration and speed reduction of each segment [44]. The larger the angular velocity of each joint of the AL, the shorter the time for each segment to complete the corresponding movement. Figs. 3 and 4 illustrate the Hip-MFAV, Hip-MOAV of the AL, Knee-MFAV, and Knee-MEAV in phase P1. The achieved results indicate that there is no statistically significant discrepancy between the DS and NS. In other words, there is no significant discrepancy between the hip and knee joints in the maximum angular velocity between the dominant side and the non-dominant sides of the attacking leg of the sub-elite taekwondo athletes in completing the movement speed in the case of the EBP guard score.

90 % of the points are scored by kicks [43] and players need fast kicks to succeed [45–47]. Furthermore, in order to generate sufficient kinetic energy for the strike to score on the EBP, the striking leg requires a high linear velocity [48,49]. The linear velocity of the leg, in turn, is a direct result of the interaction between the muscle moments and the angular momentum of the leg joint. During kicking, the angular momentum of the segments and joints of the leg is determined by the angular velocity of these segments [50].

According to Fig. 5(b), the X-axis designates that the attacking leg approaches the hitting target vertically from the left and right directions, the Y-axis represents that the hitting leg approaches the hitting target from the front and back directions, and the Z-axis describes that the attacking leg approaches the hitting target from the top and bottom directions. During phase P1, the peak hitting speed of the attacking leg on the dominant side was greater than that on the non-dominant side in the X-axis direction; further, in the P2, the discrepancy between the dominant side results and those of the non-dominant side indicates that no statistically significant discrepancy in the X-axis direction was detectable. This issue reveals that during the two strikes of the DRK, there is laterality between the DS and NS during the P1 in terms of the speed of striking the target vertically. This conclusion is consistent with the characteristics presented in Fig. 4(a) in this study, where the Knee-MFA of the AL on the DS was greater than that on the NS. The higher the Knee-MFA of the AL, the smaller the rotational inertia of the torso in the second rotation phase, and the higher the linear speed achieved by the foot based on the transmission characteristics of the swing movement in the segment movement. When using the NS leg to attack, players should magnify the Knee-MFA of the AL and build up the strength training of the muscles related to knee extension to achieve faster-striking speed and create more scoring opportunities.

4.4. Joint moment, GRF_{max}, and SI

Strengthening the ankle muscles is an effective approach to developing a dynamic balance of the limb in taekwondo athletes [51] and joint moments essentially depend on the magnitude of force generated by the contraction of the muscles or muscle groups associated with the joint [52]. Further, the maximum joint moment indicates the maximum value of moment output generated by the muscle groups during the corresponding movement of the joint, while the produced moment is related to the speed of movement of the segments at both ends of the joint [53], and as the speed of movement grows, the generated moment reduces [41,54]. The maximum joint moment of the AL could be employed as an indicator of striking power [55], and the maximum moment of knee flexion and extension of the AL has a higher impact on the strength of the strike throughout the DRK. The ability of muscles to generate force is most important to maintain body balance [56]. The DRK requires both attacking legs to complete two strikes within a short period, and the body is non-supporting after completing the first strike. At the same time, the flexion and extension moment of the knee joint plays a pivotal role in suppressing the body's COG and maintaining body balance.

The Ankle-MDM, MEFM, and MIRM on the DS are compared with those of the NS during the P2. No statistically significant discrepancy between the results obtained for the two sides mentioned above indicates that in the DRK procedure, which is a continuous exchange of striking legs, the DS and NS did not exhibit laterality due to the influence of long-term training of the athletes. It also reveals that the DRK requires symmetry for both sides. Hip-MEM of the SL on the DS was larger than that on the NS in the P2, which occurred now when the AL turned into the SL and landed after the first strike. Ankle dorsiflexion and knee flexion with hip extension after touchdown to keep the center of gravity stable and cushion the impact of the ground. Although the knee and ankle joints did not exhibit statistical discrepancies between the DS and NS in phase P2, the maximum moment magnitude of the DS was smaller than that of the NS, indicating that in controlling the COG and suppressing the ground impact, the hip joint of the dominant leg had a better performance, which relieved the impact moment of the knee and ankle joints in the vertical direction.

The ability of muscles to generate force is the most important to maintain body balance [56]. During phase P1, the peak vGRF of the SL associated with the DS is greater than that of the NS. This indicates that the SL provides a better ground force for the attack in phase P1. In phase P2, the GRF_{max} of the SL is smaller than that of the NS, and this phase is the conversion phase of the striking leg effect, and the second hit is completed during the vacating process when the attacking leg of the first hit turns into the supporting leg which has not completely landed on the ground, and the supporting leg mainly completes the cushioning of ground impact in this period. This indicates that the DS SL has a better ground impact cushioning effect during the striking leg conversion. However, for the maximum vertical ground impact force of the two strikes, there is no statistically significant discrepancy.

The symmetry index is mostly employed to quantify the discrepancy between the two sides of the limbs [57]. The larger SI indicates the greater variability between the two sides, and the discrepancy between the two sides of the SL is quantitatively assessed based on the GRF_{max} index [35]. In the P1, the DS and NS showed strong symmetry. P2 is essentially followed by completing the first air strike, the support leg for the landing buffer ground impact process, and this process supports the leg GRF_{max}, the SI = 18.84 % > 10 %. The DS and NS showed a weak symmetry, revealing that the laterality of the SL was small when providing the ground force in the P1, while in the P2, the DS and NS exhibited some laterality when the SL withstood the ground impact.

This study is not without limitations. The following deficiencies could be detectable from the present scrutiny: only data from two aerial strikes were selected for analysis, and no data analysis was conducted for the initiation and ending phases, mainly because the distance and amplitude of the subject's strikes were affected to some extent by the force measuring table and the experimental dummy. Meanwhile, the potential impact of various states (such as non-dominant and dominant legs) on sports injuries can be further analyzed; for this purpose, musculoskeletal finite element modeling can be employed to analyze the stress and strain effects on the human body, revealing potential sports injury situations [58–60].

5. Conclusion

The DRK requires more and more symmetry between the DS and NS. There exist discrepancies between the Knee-MFA of the AL and the line of attack speed of the foot in the vertical striking direction of the SL. Striking speed is the most critical factor in scoring and the DS leg has higher striking speed, athletes need to improve the striking speed of the NS leg in training. The DS and NS exhibited stronger symmetry in the symmetry index of the GRF_{max} of the SL stirrup; however, weak symmetry was attained in the peak SI of the vGRF of the SL landing cushion.

Ethical approval

This work was approved by the ethical review of Wuhan Sports University (NO. 2020048).

Funding

This study was supported by the funding of the East Lake Scholars Sponsorship Program of Wuhan Sports University in China, Hubei Provincial Department of Education of China [grant number D20194101], Natural Science Basic Research Program of Shaanxi Province [grant number 2022JQ-051], Science and Technology TeamFoundation of Wuhan Sports University [grant number 21KT02], the 14th Five-Year-Plan Advantageous and Characteristic Disciplines (Groups) of Colleges and Universities in Hubei Province [grant number 2021–05].

Data availability statement

Data included in article.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Lin Liu: Writing – original draft, Methodology, Investigation, Conceptualization. **Mengyao Jia:** Methodology, Data curation. **Yong Ma:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Shijie Lin:** Investigation, Funding acquisition, Data curation. **Qian Peng:** Investigation, Data curation. **Jun Xiong:** Resources, Funding acquisition. **Weitao Zheng:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to express their gratitude to EditSprings (https://www.editsprings.cn) for the expert linguistic services provided.

References

[1] Z. Yang, Statistical and comparative study on skill of man and women taekwondo in the 2008 Beijing olympic games, China Sport Science and Technology 45 (5) (2009) 50–53, https://doi.org/10.16470/j.csst.2009.05.021, 59.

[2] W. Dong, X. He, P. Zhou, Influence of DaeDo electronic body protect on the techniques and tactics of male taekwondo athletes in competition, Bulletin of Sport Science & Technology 21 (6) (2013) 2224, https://doi.org/10.3969/j.issn.1005 - 0256.2013.06, 10.3969/j.issn.1005 - 0256.2013.06.

[3] Z. Yang, The technical and tactical application and countermeasure of excellence taekwondo athlete of China under new rule, China Sport Science and Technology 46 (6) (2010) 77–81, https://doi.org/10.16470/j.csst.2010.06.019.
[4] N. Zhang, J. Guan, Technical and tactical characteristics of taekwondo men's 58kg champion zhao shuai in 2016 rio Olympics, Journal of Beijing Sport University 40 (2) (2017) 95–99, https://doi.org/10.19582/j.cnki.11-3785/g8.2017.02.015.
[5] S. Su, Analysis of the Use of Technique and Tactics of the Top 3 Men's Four Athletes of Taekwondo in 2016 Olympics Games, Beijing Sport University, 2018.
[6] C. Xu, W. Liu, D. Liu, et al., Effect of hitting speed of four tactical movements of taekwondo back roundhouse kick and its enlightenment for sports training, Journal of Chengdu Sport University 46 (1) (2020) 114–120.
[7] C. Zhou, D. Yu, Biomechanical characteristic analysis on elite men's Taekwondo horizontal kicking techniques, Journal of Shandong Sport University 26 (9) (2010) 58–63.
[8] Z. Hu, X. Liu, The Biomechanics Analysis on Trunk Sport at Horizontal-Kicking of Taekwondo, 01, Journal of Beijing Sport University, 2008, pp. 64–66, 81.
[9] Y. Zhang, H. Ding, J. Su, Research on influences of exercise fatigue on movement characteristics and strike speed of turning kick, J. Wuhan Inst. Phys. Educ. 54 (6) (2020) 87–94.
[10] Z. Zhang, B. Yan, S. Liu, et al., Research on the laws of the sensitive region of the sensor in the electronic protective equipment of taekwondo, Contemporary Sports Technology 8 (16) (2018) 249–251+253.
[11] A. Gutiérrez-Santiago, R. Pereira-Rodríguez, I. Prieto-Lage, Detection of the technical and tactical motion of the scorable movements in taekwondo, Physiol. Behav. 217 (2020), 112813, https://doi.org/10.1016/j.physbeh.2020.112813.
[12] S. Zhao, X. Chen, L. Guo, et al., Analysis on tactical characteristics of zhao shuaiin 2017 and 2019 World taekwondo championships, Journal of Southwest China Normal University (Natural Science Edition) 46 (10) (2021) 136–140.
[13] C. Menescardi, C. Falco, C. Ros, et al., Technical-tactical actions used to score in taekwondo: an analysis of two medalists in two Olympic Championships, Front. Psychol. 10 (2019) 2708, https://doi.org/10.3389/fpsyg.2019.02708.
[14] D. Li, X. Cheng, Y. Que, et al., Effects of inter-limb asymmetry on motor performance and intervention methods, J. Wuhan Inst. Phys. Educ. 55 (8) (2021) 94–100.
[15] J. Ma, Z. Wang, F. Hu, et al., Effect of lower-limb dominance and non-dominance shuttle runs under load carriage on the balance responses in young cadets, Chin. J. Appl. Physiol. 34 (4) (2018) 350–354.
[16] M. Helme, J. Tee, S. Emmonds, et al., Does lower-limb asymmetry increase injury risk in sport? A systematic review, Phys. Ther. Sport 49 (2021) 204–213, https://doi.org/10.1016/j.ptsp.2021.03.001.
[17] Y. Li, P. Huang, H. Wang, et al., Dominant and non-dominant side knee isokinetic characteristics of Chinese calisthenics athletes, Chinese Journal of Tissue Engineering Research 25 (2) (2021) 232–236.
[18] Y. Shao, J. Zhang, M. Jiang, et al., Kinematics characteristics of lower limb joints of young men running wearing knee pads, Chinese Journal of Tissue Engineering Research 26 (6) (2022) 832–837.
[19] X. Mao, Q. Zhang, G. Wang, et al., Biomechanical laterality effect between the dominant and non-dominant during running support phase, Journal of Capital University of Physical Education and Sports 29 (1) (2017) 91–96.
[20] Y. Zhang, A. Lu, Performance of dominant-side and non-dominant-side in the continuous vertical jump landing stage, China Sport Science 33 (5) (2013) 68–73.
[21] M. Liu, Z. Zhou, X. Ma, et al., Effect of circuit training on muscle strength of lower limbs and BalanceAbility in overweight and obese elderly women, Journal of Wuhan Sports University 55 (6) (2021) 95–100.
[22] B. Li, W. Li, An experimental study of influences of weighted squat and Bulgarian squat in hockey Players'Moving ability, Journal of Wuhan Sports University 55 (5) (2021) 73–78.
[23] K. Fousekis, E. Tsepis, G. Vagenas, Lower limb strength in professional soccer players: profi-le, asymmetry, and training age, J Sport Sci Med 9 (3) (2010) 364–373.
[24] V.V. Romanenko, O.O. Podrihalo, L.V. Podrigalo, et al., The study of functional asymmetry in students and schoolchildren practicing martial arts, Phys Educ Stud 24 (3) (2020) 154–161, https://doi.org/10.15561/20755279.2020.0305.
[25] I.M. Miziara, B.G. da Silva, I.A. Marques, et al., Analysis of the biomechanical parameters of high performance of the roundhouse kicks in Taekwondo athletes, Res Biomed. Eng 35 (3) (2019) 193–201.
[26] Y. Guan, Inter-limb Asymmetries in Functional Performance and Non-contact Lower-Limb Injury in Pediatric-Age Athletes, UBC, 2021.
[27] Y. Li, Rotating Mechanical Analysis of Taekuondo Yeop-Jireugi, 03), Journal of Wuhan Sports University, 2003, pp. 55–58.
[28] A. Lu, J. Dai, S. Liu, Joint strength of non dominant side of lower limbs in badminton teenage players, Journal of Beijing Sport University 39 (7) (2016) 131–138.
[29] Y. He, J.P. Pang, Development trend of men's taekwondo techniques and tactics under new rules: taking World champion lee dae-hoon as an example, Journal of Wuhan Sports University 53 (12) (2019) 82–87, https://doi.org/10.15930/j.cnki.wtxb.2019.12.012.
[30] Aloui, A., Tayech, A., Mejri, M. A., et al. Reliability and validity of a new taekwondo-specific change-of-direction speed test with striking techniques in elite taekwondo athletes: A pilot study. Front. Physiol. 13:774546. https://doi.org/10.3389/fphys.2022.774546.
[31] B. Jin, Q. Liu, Analysis on the characteristics of the start and the initial scoring in men's taekwondo at the 29th Olympics, Journal of Chengdu Sport University 38 (6) (2012) 56–59, https://doi.org/10.15942/j.jcsu.2012.06.016.
[32] Ojeda-Aravena, A., Herrera-Valenzuela, T., Valdés-Badilla, P., et al. Inter-individual variability of a high-intensity interval training with specific techniques vs. repeated sprints program in sport-related fitness of taekwondo athletes. Front. Physiol. 12:766153. https://doi.org/10.3389/fphys.2021.766153.
[33] R.L.M. Souza, F.J. Aidar, R. Villar, et al., Assessment of asymmetry at different intensities between conventional and paralympic powerlifting athletes, Heliyon 9 (5) (2023), https://doi.org/10.1016/j.heliyon.2023.e16211.
[34] C. Phuaklikhit, T. Junsri, The correlation of centre of mass evaluation utilising accelerometry-based measurement and the clinical dynamic balance test in professional football athletes with chronic ankle instability, Heliyon 9 (6) (2023), https://doi.org/10.1016/j.heliyon.2023.e17318.
[35] H. Liu, W. Fu, X. Wu, et al., Biomechanics Research on laterality effectbetween dominant and non-dominantLeg during single leg landing, China Sport Science 34 (8) (2014) 70–76.
[36] J. Su, Y. Zhang, The biomechanical features analysis of turning kick techniques in different-weight-class taekwondo athletes, Journal of Xi'an Physical Education University 36 (2) (2019) 220–226.
[37] Q. Peng, Y. Ma, L. Liu, M. Jia, Biomechanical Characteristics of Taekwondo Athletes' Whirlwind Kick Technique under the Score of Daedo Electronic Protective Equipment.Summary Collection of Papers of the 12th National Sports Science Conference-Special Report (Sports Biomechanics Branch), 2022, pp. 161–162.
[38] R.O. Robinson, W. Herzog, B.M. Nigg, Use of force platform variables to quantify the effects of chiropractic manipulation on gait symmetry, J. Manip. Physiol. Ther. 10 (4) (1987) 172–176.
[39] D.R. Mailapalli, J. Benton, T.W. Woodward, Biomechanics of the taekwondo axe kick: a review, J Hum Sport Exerc 10 (1) (2015) 141–149.
[40] J. Wsik, The structure and influence of different flying high front kick techniques on the achieved height on the example of taekwon-do athletes, Arch Budo 8 (1) (2012) 45–50.
[41] D. Dong, H. Guo, W. Wang, The sEMG properties of backward kicking of elite men's taekwondo athletes in national team, Journal of Beijing Sport University 36 (4) (2013) 68–71, https://doi.org/10.19582/j.cnki.11-3785/g8.2013.04.014.
[42] S. Shenoy, P. Mishra, J.S. Sandhu, Peak torque and IEMG activity of quadriceps femoris muscle at three different knee angles in a collegiate population, J Exerc Sci Fit 9 (1) (2011) 40–45, https://doi.org/10.1016/S1728-869X(11)60005-1.
[43] M. Kazemi, G. Perri, D. Soave, A profile of 2008 Olympic Taekwondo competitors, J. Can. Chiropr. Assoc. 54 (4) (2010) 243.
[44] J. Su, Biomechanical analysis of ankle movement risk when whip-kickHitting different types of objects, Journal of Wuhan Sports University 49 (10) (2015) 62–68.
[45] P.V.S. Moreira, L.F. Crozara, M.F. Goethel, et al., Talent detection in taekwondo: which factors are associated with the longitudinal competitive success? Arch Budo (2014) 295–306.

[46] C. Falco, O. Alvarez, I. Castillo, et al., Influence of the distance in a roundhouse kick's execution time and impact force in Taekwondo, J. Biomech. 42 (3) (2009) 242–248, https://doi.org/10.1016/j.jbiomech.2008.10.041.
[47] N. Jakubiak, D.H. Saunders, The feasibility and efficacy of elastic resistance training for improving the velocity of the Olympic Taekwondo turning kick, Jscr 22 (4) (2008) 1194–1197, https://doi.org/10.1519/JSC.0b013e31816d4f66.
[48] N. Tasika, Reliability & linearity of an electronic body protector employed in taekwondo games: a preliminary study, J Hum Sport Exerc 8 (3) (2013) S622S632, https://doi.org/10.4100/jhse.2013.8.Proc3.08.
[49] I. Estevan, C. Falco, Mechanical analysis of the roundhouse kick according to height and distance in taekwondo, Biol. Sport 30 (4) (2013) 275–279.
[50] F. Quinzi, P. Sbriccoli, J. Alderson, et al., Intra-limb coordination in karate kicking: effect of impacting or not impacting a target, Hum Movement Sci 33 (2014) 108–119, https://doi.org/10.1016/j.humov.2013.07.021.
[51] H.M. Lee, S. Oh, J.W. Kwon, Effect of plyometric versus ankle stability exercises on lower limb biomechanics in taekwondo demonstration athletes with functional ankle instability, Int J Env Res Pub He 17 (10) (2020) 3665, https://doi.org/10.3390/ijerph17103665.
[52] S. Kim, M. Miller, A. Tallarico, et al., Relationships between physical characteristics and biomechanics of lower extremity during the squat, J Exerc Sci Fit 19 (4) (2021) 269–277, https://doi.org/10.1016/j.jesf.2021.09.002.
[53] S. Harbili, E. Harbili, Z. Aslankeser, Comparison of bilateral isokinetic and isometric strength differences in elite young male and female taekwondo athletes, J Exerc Rehabil 18 (2) (2022) 117, https://doi.org/10.12965/jer.2244122.061.
[54] J. Su, Y. Zhang, S. Ma, Effects of hitting velocity of different level sanda athletes; whip-leg movement, Journal of Wuhan Sports University 52 (1) (2018) 87–94.
[55] K. Buśko, P.T. Nikolaidis, Biomechanical characteristics of taekwondo athletes: kicks and pu-nches vs. laboratory tests, Biomed. Hum. Kinet. 10 (1) (2018) 81–88.
[56] Q. Wang, L. Li, M. Mao, et al., The relationships of postural stability with muscle strength and proprioception are different among older adults over and under 75 years of age, J Exerc Sci Fit 20 (4) (2022) 328–334, https://doi.org/10.1016/j.jesf.2022.07.004.
[57] X. Ma, W. Sun, A. Lu, et al., The improvement of suspension training for trunk muscle power in Sanda athletes, J Exerc Sci Fit 15 (2) (2017) 81–88, https://doi.org/10.1016/j.jesf.2017.09.002.
[58] Y. Song, X. Cen, H. Chen, et al., The influence of running shoe with different carbon-fiber plate designs on internal foot mechanics: a pilot computational analysis, J. Biomech. 153 (2023), 111597, https://doi.org/10.1016/j.jbiomech.2023.111597.
[59] D. Sun, Y. Song, X. Cen, et al., Workflow assessing the effect of Achilles tendon rupture on gait function and metatarsal stress: combined musculoskeletal modeling and finite element analysis, P I Mech Eng H 236 (5) (2022) 676–685, https://doi.org/10.1177/09544119221085795.
[60] A. Navacchia, D.R. Hume, P.J. Rullkoetter, et al., A computationally efficient strategy to estimate muscle forces in a finite element musculoskeletal model of the lower limb, J. Biomech. 84 (2019) 94–102, https://doi.org/10.1016/j.jbiomech.2018.12.020.