Biomechanical characteristics of the Axe Kick in Tae Kwon-Do

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B Data Collection
C Statistical Analysis
D Manuscript Preparation
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Abstract

Background and Study Aim: In the current literature, few scientific studies can be found related to the biomechanical characterization of the Axe Kick – one powerful Tae Kwon-Do kick. This study aimed to supply the kinematics of an effective axe kick by quantifying the skill using 3D motion capture technology and full body biomechanical modelling.

Material/Methods: A 3D motion-capture system with four camcorders (60 frames/s, SIMI motion 7.3) was used to measure full-body movement of 12 subjects (4 professionals & 8 advanced fighters). The measured data was used to build 14 segmental biomechanical modelling for obtaining parameters such as coordinates, ranges of motion and speeds of joints. Statistical T-tests were used to determine the kinematic differences between the two groups in order to quantify the effective way for conducting the skill.

Results: There are significant differences existing in the flexibility of hip, knee control of the kicking leg as well as time used for lifting and downward drive of the foot. These differences may be used to account for the 15% difference observed in action time, 12% in maximal kick height and 20% in maximal drive speed of the kick foot between professional and advanced fighters.

Conclusions: An axe kick can be characterized as a whip-like kicking movement during leg lift and an axe-like movement during the downward drive of the heel. Hip flexibility, muscle power and whip-like movement are keys to the kick quality.

Key words: 3D motion capture • full-body biomechanical modelling • hip flexibility • whip-like movement

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Background

Tae Kwon-Do is a type of unarmed combat designed for self-defence. Practice of this sport is built upon fundamental techniques such as striking, blocking and kicking. Currently, Tae Kwon-Do is widely practiced in more than 120 countries on five continents, owing much of its popularity to its teachings of self-strength, self-confidence, and self-control [1].

The name Tae Kwon-Do means "the art of kicking and punching". Accordingly, this form of martial art is famous for its powerful kicking techniques [2], which can possess enough force to break bones and bricks. Some of the best known Tae Kwon-Do kicks include Front Kick, Turning (or Roundhouse) Kick, and Axe (or Downward) Kick.

The Front Kick has been the subject of the majority of biomechanical research [3–9]. It is characterized by a proximal to distal sequential motion with a fast unloaded movement to maximize kick foot velocity [6]. The effectiveness of the kick is influenced by target height. A recent study revealed that there are four main factors influencing the height achieved by an athlete: centre of

Figure 1. Stages of an Axe Kick (figure was created by using 3D motion capture data and biomechanical model of this study).

gravity (COG) at take-off, the flight height of the COG, the leg length and the angle formed between the plane perpendicular to the board and the leg [8].

The next well-studied kick is the Turning Kick [9–12]. The Turning Kick is the most frequently used technique in Tae Kwon-Do competitions [11]. It employs a motor control pattern similar to the Front Kick, but uses additional body rotations to produce great velocity and impact force. More specifically, the Turning Kick is initiated in the torso, with trunk rotation supplying energy to the thigh, and finished by knee extension shortly before reaching the target [12].

The Side Kick has lately become a subject of biomechanical analysis [13,14]. If applied at the right moment during a competition, a single Side Kick may reveal the winner [14]. The determining factor – foot velocity – depends heavily on the development of knee velocity during leg lifting [13].

One powerful Tae Kwon-Do kick that has not been biomechanically characterized in Science Citation Index (SCI) journals (Web of Knowledge, Thomson Reuters, USA) is the Axe Kick. Although there are a few studies published in conferences proceedings or non-SCI journals [9,15–17], a holistic view of biomechanical characteristics has not been revealed. Existing studies have either supplied partial perspective on the kick due to:

1. Limitations of measuring technology applied (i.e. using accelerometers instead of 3D motion capture) [15,17] and
2. Partial body model (i.e. 3D capture focusing on kicking foot) [9]

or revealed the relevant factors for injury prevention rather than the overall control characteristics [16]. Therefore, studies using 3D, full-body biomechanical analysis are needed to add missing knowledge into our understanding of the skill for coaches and practitioners.

The Axe Kick is most useful when an opponent is open in the upper body region. To execute the kick, the fighter brings up his/her kicking leg in a circular motion, and at the peak height, brings the heel straight down (like a downward movement of an axe) upon the opponent's shoulder or head. Another use for the Axe Kick is to stop an incoming attack. The fighter can target an Axe Kick against the supporting thigh of an opponent in the initial stages of a kick.

The Axe Kick is executed in four stages. Stage one, the Decoy, is optional and meant only to confuse the opponent with regards to which leg is the kicking leg and, in turn, create an opening for the target. The fighter executes a rapid stance change, followed immediately by the next stage: The Power Load. In this second stage, the fighter raises the kicking leg in a slight medial circular motion, building power for the ensuing kick by pre-lengthening the kicking muscles. The velocity of the upward motion, as well as the height of the kicking heel will determine the force of stage three: The Drive. Here, the fighter positions the heel of the kicking foot directly above the target area as the heel reaches peak height. The circular motion is stopped and all the energy derived from the Power Load is transferred to the Drive downward into the opponent. Finally, stage four, the Landing & Stabilization, returns the fighter to a stable stance so further techniques can be performed (Figure 1).

In this study, we aim to identify factors instrumental to the success and effectiveness of an Axe Kick. Based on how such kicks are executed, we hypothesize that such factors are related to the following three aspects of the Axe Kick:

1. The maximum target height: the height at which an athlete can make an attack is determined by the anthropometry of the fighter (e.g. body height and leg length) and the flexibility of the fighter.

2. The inertia of the kicking leg: For an Axe Kick to be effective, all movements of the kicking leg need to have minimal execution time. Thus the dynamic posture / kinematics of the kick should minimize the moment of inertia of the kicking leg during the Power Load phase.
3. The speed of the kicking foot: The power of the Axe Kick is directly determined by the speed of the kicking foot, as it drives downward toward its target. Thus the degree of extension of the kicking leg and its angular velocity should maximize the speed of the kicking foot.

All three aspects can be quantified using 3D motion capture technology and full-body biomechanics modelling. Thus for the first time, we report full-body three-dimensional analysis on highly-skilled Tae Kwon-Do athletes (college varsity and professional fighters) and supply information on normative characteristics of the group. The aims of the current study are: to capture the full-body movement of the axe kick in three-dimensions; to apply a 14-segment, full-body model to reveal the timely kinematic characteristics of this skill; to explore parameters that can be used to quantitatively evaluate the Axe Kick and to reveal the kinematic/anthropometrical conditions for kick effect. Such information can assist with the design of training programs based on quantitatively determined 'ideal' factors. Attention to these at the earliest stages of skill acquisition can help coaches create goal-oriented drills, likely enhancing the learning process.

Material and Methods

Two groups of male subjects were measured: an advanced group (n=8) and a professional group (n=4). The advanced group consisted of sport students from China and Canada with an average age of 21.3 years (±1.6) and over 5-year experience. The average body heights and weights were 1.78 m ±0.08 and 68.6 kg ±6.3 respectively. The professional group had an average age of 23.4 years (±1.2) and over 15-year experience including an average of 4.8±1.2 years of professional experience. They were national-level athletes from a provincial team in China. The average body heights and weights of the professional group were 1.81 m ±0.04 and 63.0 kg ±3.9 respectively. After individualized warm-up, each subject completed three WTF-style axe kicks.

A 3D motion-capture system with four camcorders (SIMI motion 7.3) was used to measure full-body movement at 60 frames/s. The four camcorders were placed on each corners of a square (side length: 10 meters). This setup yielded a capture area of 5×5 m^2. The kinematic data collected supplied primary information, such as joint position and their changes, velocities, and accelerations for full-body modelling. The capture area was calibrated by 24 markers. Calibration residuals were determined in accordance with SIMI's guidelines and yielded positional data accurate within 5 mm. Motion capture technology permits considerable freedom of movement for the subject without negatively influencing accuracy of data. Taking advantage of this, we placed no restrictions

Table 1. Dominant parameters that show the significant differences (p<0.05) of the axe kick between advanced and professional fighters.

	Dominant patameters	Advanced		Professional	
		Mean	StDev	Mean	StDev
Flexibility	H_{Max} (%BH)	124.9%	17.0%	137.1%	6.2%
	α_{Thighs}	148.8	6.1	173.5	3.6
Kinematics of the Power Load (Stage 2)	Hip_{Rom} (°)	183.6	8.9	206.1	9.7
	$Knee_{Rom}$ (°)	27.4	8.3	99.6	6.7
	T_2 (s)	0.41	0.05	0.35	0.02
	V_{Max} (m/s)	8.7	0.7	11.4	1.1
Kinematics of the Drive (Stage 3)	Hip_{Rom} (°)	122.4	5.7	139.1	6.2
	T_3 (s)	0.35	0.04	0.31	0.01
	V_{Max} (m/s)	9.1	0.7	10.9	1.2
Action	T_{Total} (s)	0.76	0.09	0.66	0.03

StDev – standard deviation; H_{max} – the maximal kick height normalized by BH (body height); α_{Thighs} – the maximal angle between thighs during the Power Loading (stage 2); Hip_{ROM} – the range of motion (ROM) of the hip; $Knee_{ROM}$ – the range of motion (ROM) of the knee; V_{max} – maximal speed of ankle; T_2 – cduration of Stage 2; T_3 – duration of Stage 3; T_{Total} – total time.

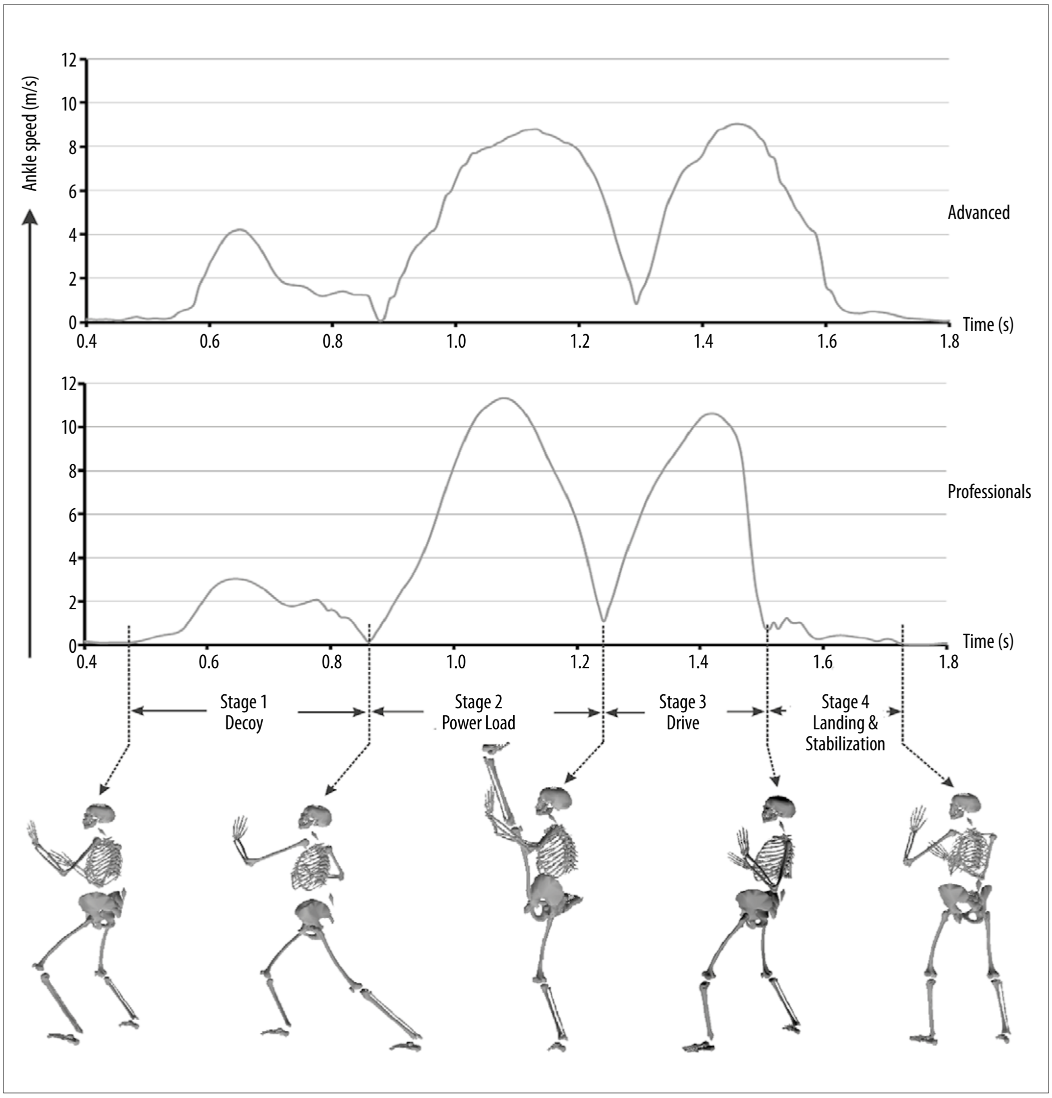

Figure 2. Two typical control patterns – Quantification of the ankle speed (kick leg) during an axe kick with stages' identifications and the dynamic postures at begin and end of each stage.

on subjects' movements within the capture volume in an effort to preserve their normal "style".

Raw kinematic data was processed using a five-point (1-3-4-3-1 function) smoothing filter and the resultant data was input into the 15-segment biomechanical model [18,19]. Segment lengths, joint angles, and ranges of motion (ROMs) for the joints were determined. Model segments are identified as follows: head, upper trunk, lower trunk, upper arms, lower arms, hands, thighs, shanks and feet. A characterized motion of the model is shown in Figure 1. The definitions of Nordin & Frankel [20] were used for determining joint flexion/extension, abduction/adduction and rotation (twist).

All parameters obtained from 3D motion capture and biomechanical modelling were analysed using Excel (Microsoft, USA). Results are presented using basic descriptive statistics and, where appropriate, T-tests to contrast differences between the advanced subjects and the professional athletes. Statistical significance is defined as $p<0.05$. Indications of an "increase" in a parameter (percentage change) is calculated using the formula [(large value – small value)/the small value]. This formula is also used for determining the percentage differences between groups.

Results

3D motion analysis revealed distinguishable differences of lower body movement between advanced and professional fighters. For contrasting the main distinctions, only the parameters that had statistical T-tests revealed significant differences ($p<0.05$) were selected and shown in Table 1 (labelled as dominant parameters). It should be noted that the ankle marker was used (instead of using heel marker) to quantifying kicking foot kinematics due to the following fact: Our initial data analysis indicated that the ankle marker was a better reference than the heel marker in determining the kicking foot kinematics, because the marker minimized the influence of ankle control variation on foot movement among our test subjects.

Comparing the maximal kick height (Hmax, normalized as percentage of body height [BH]), the difference between the two groups reached an average of 12.2%BH (124.9% *vs.* 137.1%, Table 1). This percentage value represented an average of 0.25 m difference in the maximal kick height between the advanced and professional fighters. As for the maximal angle between thighs at the end of the Power Loading (α_{Thighs}), the professionals had a mean value of 173.5°, while the advanced fighters had only 148.8°, a decrease of 24.7° or 16.6%.

During the Power Loading stage, the professional fighters showed significantly higher ROMs for both hip and knee rotation. The ROMs for the professional fighters reached an average of 206.1° and 99.1° for hip and knee respectively, while they were only 183.6° and 27.4° for the advanced fighters. Even though the professional fighters experienced bigger ROMs of hip and knee rotation than advanced fighter, the time that the professionals needed for the Power Loading (T_2) was significantly shorter than their counterpart. In average, the professional fighters finished the Power Loading stage around 0.35 seconds, while their counterpart needed 0.41 seconds to finish the stage. As a result, the professional fighters generated a higher maximal speed during the Power Loading (V_{max}=11.4 m/s) than the advanced fighters (V_{max}=8.7 m/s, Table 1 and Figure 2).

Comparing the kinematics of the Drive stage, similar tendencies to the Power Loading stage were found between the both subject groups except for the knee control. Namely, professional fighters underwent a larger ROM for the extension of the hip than their counterpart (139.1° *vs.* 122.4°) by using significant shorter time (0.31 s *vs.* 0.35 s). Consequently, the professional fighters generated a higher maximal speed than their counterpart during the Drive stage (10.9 m/s *vs.* 9.1 m/s, Figure 2). However, there was no significant difference that existed for knee control, i.e. both groups drove the kicking leg down with an extended knee.

For the total action time (the Power Loading and the Drive), professional group performed the skill significantly faster than their counter part (0.66 s *vs.* 0.76 s, Table 1 and Figure 2), i.e. the professional shorted the action time by 15%.

Discussion

One aim of this study was to quantitatively describe the kinematic characteristics of the Tae Kwon-Do axe kick using a 3D full-body model. Results reveal that the hip flexibility contributes notably to skill effectiveness. Firstly, a professional fighter will utilize a larger ROM of hip flexion/extension to reach a higher kick height. Such a control can hardly be done by an athlete with limited hip flexibility. Secondly, the extreme angle between the two thighs at the end of the Power Loading (α_{Thighs}) provides initial conditions that increase lengths of hip flexors prior to their contraction. This dynamic muscle pre-lengthening should generate larger muscle forces based on length-tension relationships of the muscles, increasing the effectiveness of kicking. As revealed by Gowitzke & Milner [21], a pre-lengthening of 120–130% (measured from resting length) leads to maximum muscle tension. From this, we suggest that a quantification of muscle lengths is needed in order to determine whether large α_{Thighs} (high flexibility) leads to the generation of a maximal force during kicking. This will require further studies.

Collectively, these findings suggest that full-body 3D analysis provides an effective means to examine the axe kick. The significant differences between the two tested groups in Hmax (12.2% BH or 0.25 m) leads us to conclude that the hip flexibility is a key factor in increasing the quality of an axe kick.

The results also confirm that significant differences exist between the two levels of fighters with regard to knee control. During the Power Loading stage, although professional fighters have to experience a larger hip ROM than their counterpart (206.1° *vs.* 183.6°), they finish the stage significantly faster (0.35 s *vs.* 0.41 s, i.e. 17% shorter) than their counterpart. The control of knee flexion/extension likely contributed to the resulting differences, although possible differences in muscle power generation were not assessed between fighters. A quick knee flexion and extension during the Power Loading stage was observed in the professional group, while this characteristics was almost absent in our advanced subjects. One effect of the knee flexion during a leg forward swing is to reduce the moment of inertia (i.e. reducing the leg's resistance to rotation), which results in a faster swing. An estimation of such an advantage is as follows: Using the measured kick leg kinematics, the average body height (1.80 m) and body weight (65 kg) of the tested subjects as well as anthropometrical estimation method (19), the moment of inertia was calculated for the kick leg of the professionals (α_{knee}=80°, average of the professionals) and the advanced fighters (α_{knee}=153°, average of the advanced fighters). The results suggested a maximum difference of 42% between both groups, i.e. professionals decrease notably their leg moment of inertia in comparison to advanced fighters during the up-swing of the kick leg. These results lead us to conclude that the knee control is another key factor in increasing axe kick quality.

Concentrating on the ankle speeds of both the Power Load and the Drive (Figure 2), we observe two discrete differences between the two groups. The first shows a shorter Drive for professionals even though there is similar knee control (extended knee during the Drive) for both groups; and the second is the ankle of professionals undergoing its fastest motion during the Power Load, while the ankle of advanced fighters have the highest speed during the Drive. Since the professions have a larger hip ROM during the Drive than advanced fighters, the first difference indicates that the professionals possess more powerful leg muscles that the advance fighters. As for the second, due to the leg swing against gravity, the ankle speed should be lower during the Power Load than that during the Drive. Three factors may contribute to the reversed result of the professionals: smaller moment of inertia (larger knee flexion), stronger hip flexors and bigger hip ROM in comparison to advanced fighters. The kick leg kinematics of the professionals suggests that shortest motion/fastest speed of ankle movement is typically achieved through whip-like movements [18], whereby the femur and tibia/fibula move in sequential motion in a proximal to distal pattern, i.e. two phases involved: the first is one of fast hip flexion and the second includes fast knee extension. Summarizing the above, the leg is one of the larger segments of the body. It is very important for the fighters to be able to move this segment as quickly as possible in order to execute an axe kick that is not easily blocked or recognized [22]. In doing so, during the Power Load, a fighter should begin a rapid knee lift of the kicking leg followed by knee flexion. This action serves to reduce the Moment of Inertia of the kick leg for a much quicker Power Load. During the Drive, the knee should remain almost fully extended during the powerful extension of the kicking side hip, positioning the heel of the kicking foot directly above the target area, as such transferring the Drive energy downward into the opponent.

Conclusions

In conclusion, using 3D motion capture and full-body modelling, we can quantify the axe kick as a whip-like kicking movement during the Power Load and its axe-like movement during the Drive. The goals of the Power Load are to reach a possible highest heel position in a possible shortest time and to pre-lengthen kick leg muscles for a more powerful muscle contraction. The aim of the Drive is to transfer as much energy downward into the opponent using a heel attack with a nearly straight leg. Effective axe kicking involves Hip and knee coordination. Our study suggests that hip flexibility, muscle power and whip-like movement of the kicking leg are keys to the kick quality. The combined effect of these keys may be used to account for the 15% difference observed in action time, 12% in maximal kick height and 20% in maximal drive ankle speed between professional and advanced fighters.

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