©Journal of Sports Science and Medicine (2016) **15,** 92-101
http://www.jssm.org

Research article

A Kinematic Analysis of the Jumping Front-Leg Axe-Kick in Taekwondo

Emanuel Preuschl ✉, Michaela Hassmann and Arnold Baca
University of Vienna, Institute of Sport Science, Department of Biomechanics, Kinesiology and Applied Computer Science, Vienna, Austria

Abstract
The jumping front-leg axe-kick is a valid attacking and counter-attacking technique in Taekwondo competition (Streif, 1993). Yet, the existing literature on this technique is sparse (Kloiber et al., 2009). Therefore, the goal of this study was to determine parameters contributing significantly to maximum linear speed of the foot at impact. Parameters are timing of segment and joint angular velocity characteristics and segment lengths of the kicking leg. Moreover, we were interested in the prevalence of proximal-to-distal-sequencing. Three-dimensional kinematics of the kicks of 22 male Taekwondo-athletes (age: 23.3 ± 5.3 years) were recorded via a motion capturing system (Vicon Motion Systems Limited, Oxford, UK). The participants performed maximum effort kicks onto a rack-held kicking pad. Only the kick with the highest impact velocity was analysed, as it was assumed to represent the individual's best performance. Significant Pearson correlations to impact velocity were found for pelvis tilt angular displacement ($r = 0.468$, $p < 0.05$) and for hip extension angular velocity ($r = -0.446$, $p < 0.05$) and for the timing of the minima of pelvis tilt velocity ($r = -0.426$, $p < 0.05$) and knee flexion velocity ($r = -0.480$, $p < 0.05$). Backward step linear regression analysis suggests a model consisting of three predictor variables: pelvis tilt angular displacement, hip flexion velocity at target contact and timing of pelvic tilt angular velocity minimum (adjusted $R^2 = 0.524$). Results of Chi-Squared tests show that neither for the leg-raising period ($\chi^2 = 2.909$) of the technique, nor for the leg-lowering period a pattern of proximal-to-distal sequencing is prevalent ($\chi^2 = 0.727$). From the results we conclude that the jumping front-leg axe-kick does not follow a proximal-to-distal pattern. Raising the leg early in the technique and apprehending the upper body to be leant back during the leg-lowering period seems to be beneficial for high impact velocity. Furthermore, striking by extending the hip rather than by flexing the knee could raise impact velocity.

Key words: Biomechanics, motion analysis, martial arts, timing, kicking velocity, joint angles

Introduction

Akin to boxing or other full-contact combat sports a taekwondo match is generally won by knockout or by points. Valid points are scored by punches to the torso and kicks to the torso or the head of the opponent (World Taekwondo Federation, 2015). Compared to punches kicking techniques are more likely to score in taekwondo competition (Kazemi et al., 2006). This preference of leg skills is a stylistic peculiarity of taekwondo in comparison to karate or wushu (Ahn et al., 2009). Streif (1993) published the results of a Korean survey on the point-scoring techniques of several Korean tournaments held in 1983. He quoted that 4.5% of points were scored with the axe-kick, which is therefore taking the third place in the ranking of the most successful techniques. Recent data by Matsushigue et al. (2009) on Brazilian national competition suggest that round kick and side kick are more frequent techniques. Winners perform fewer direct attacks than nonwinners (Menescardi et al., 2015), but none of the used kicking techniques are specified.

Park (1999) describes the axe-kick as follows: "The kicking foot is swung up across the body until it is high in the air, then it is brought straight down onto the target." For a more detailed technique description refers to Preuschl and Attarpour (2014). This technique is executed with the front leg (nearer to the opponent) in a jumping motion. Take-off is followed by a hip and knee flexion movement, raising the striking leg. By using trunk and hip extension and slight knee flexion movement the foot returns from its high position into a down- and forward motion, striking the opponent's scull, face or clavicle with the heel or the sole of the foot (see Figure 1). The change in angular direction of the joints' movements sets the axe-kick apart from pushlike or throwlike kicking movements as the leg's momentum is stopped and reversed rather than transferred to another plane (Kim et al., 2011).

Performance parameter

In WTF competition rules, article 18 describes the procedure in the event of a knock down as follows: "1.4. When a contestant who has been knocked down cannot demonstrate the will to resume the contest by the count of 'Yeo-dul (eight)', the referee shall announce the other contestant winner by RSC (Referee Stops Contest)" (World Taekwondo Federation, 2015, p. 39). The effect of a martial arts strike is often linked to peak impact force or transferred linear momentum (Falco et al., 2009; Gulledge and Dapena 2008; O'Sullivan et al., 2009; Walilko, et al. 2005).

Blum (1977) theorised on the physics of martial arts board breaking that "an adept practitioner is able to combine the high speed and high effective mass necessary to achieve success in multiboard breaking". Pearson (1997) stated that a higher linear velocity at initial target contact correlates with a higher mean impact force ($r = 0.66$, $p < 0.05$) in taekwondo roundhouse kicks. To find out what contributes to "high speed" (Blum 1977) in a jumping front-leg axe-kick, Kloiber et al. (2009) investigated the influence of several kinematic parameters on vertical linear velocity of the ankle at initial target contact and found positive correlation for the hip extension angle

Received: 19 June 2015 / Accepted: 14 December 2015 / Published (online): 23 February 2016

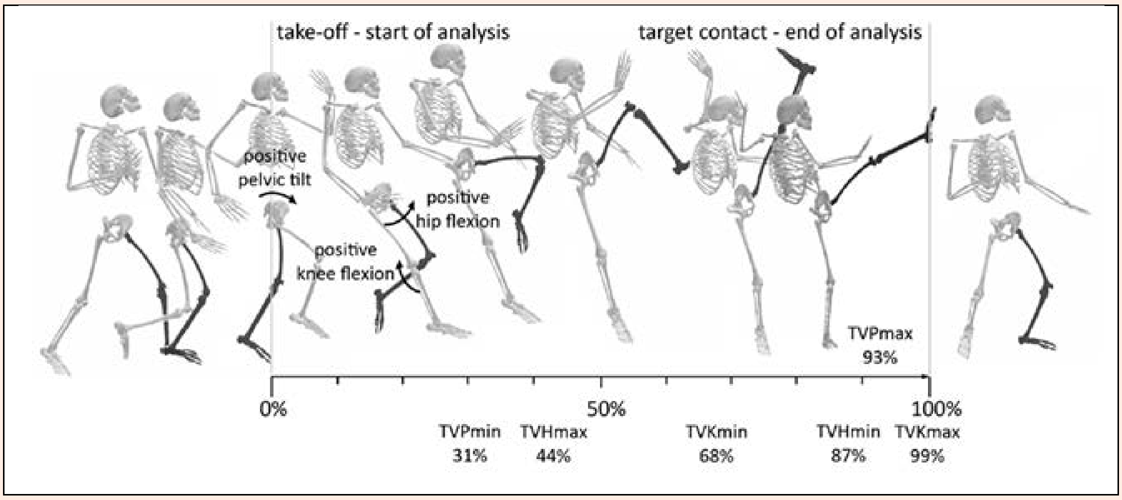

Figure 1. Sequential image of a jumping front-leg axe-kick. The variables TVPmin, TVHmax, TVKmin, TVHmin, TVPmax, TVKmax indicate the timing of segment and joint angular velocity peaks. They are ordered sequentially according to mean/median timing (normalized time) of the participants' jumping front-leg axe-kicks. A short description is given in Table 1. Definitions are given in subchapter 'Temporal and kinematic parameters'. (adapted from Kloiber et al. 2009).

between maximum stretch and initial target contact ($r = 0.542$, $p < 0.05$). In a match of taekwondo, the foot doesn't necessarily have to hit the opponent in vertical direction as valid target areas are also the face and the sides and back of the head (World Taekwondo Federation, 2015). Consequently, not only the vertical component, but all the ankle velocity components contribute to the kick's impact energy. Therefore, the Euclidean norm of all 3 dimensions of impact velocity (IV) should be selected to quantify performance.

Anthropometric parameters

In martial arts, studies on body composition and physiological profiles have been performed by several authors (Heller et al. 1998, Khanna and Manna 2006, Smith 2006). Kazemi et al. (2006) found non-significant differences between successful and non-successful fighters in the 2004 Olympics' tournament and concluded that "winners overall tended to be younger in age and taller with slightly lower BMI than their weight category average". In De Witt and Hinrichs' (2012) deterministic model of factors contributing to a soccer kick's ball velocity, segment lengths are taken into consideration to affect peak linear velocity of the distal joints and therefore ball velocity. However, a segment's moment of inertia depends on its length and mass. Changes of these parameters could affect an athlete's ability to accelerate a respective segment around its proximal axis. Anthropometric parameters that have hence been selected for investigating their contribution to impact velocity are body mass BM, as well as thigh length TL and shank length SL of the kicking leg.

Temporal and kinematic parameters

According to Putnam (1993), throwing and striking movements are generally classified according to their "proximal-to-distal sequencing". The author stated that proximal-to-distal sequencing of striking and throwing motions could be described either by the characteristics of the technique's linear velocities of segment endpoints, joint angular velocities or segment angular velocities. Proximal-to-distal sequencing is determined by the successive occurrence of segmental velocity extrema. Putnam also stated that at least one angle must be a segment angle that is measured relative to the laboratory's coordinate system if joint angular velocities are considered. Timing of peak joint angular velocities were investigated by Van den Tillaar and Ettema (2007) for their relation to ball release velocity in overarm throwing of experienced handball players. Based on analogous considerations we calculated timing of the angular velocities of the pelvis segment, hip joint flexion and knee joint flexion to determine the proximal-to-distal sequencing and to study their impact on IV.

Kellis and Katis (2007) review research on instep soccer kicking. They report that flexion/extension angles and angular velocities of the hip, knee and ankle joints as well as rotation of the pelvis have been investigated by several authors in order to describe kicking kinematics (Levanon and Dapena, 1998; Nunome et al., 2002). In their effort to investigate different taekwondo kicks, Kim et al. (2011) used a model of pelvis, thigh and shank and calculated flexion/extension, abduction/adduction and internal/external rotation of the hip. For the knee joint, only flexion and extension were determined. The angular displacement of the pelvis was calculated relative to the global coordinate system. In a roundhouse kick knee flexion angular velocity correlates significantly with impact force (Pearson, 1997). Tsai et al. (2005) investigated knee joint angles in a front-leg axe-kick at three different instants. For the back-leg axe-kick, Tsai et al. (2004) investigated angular displacement and velocity of the knee and hip. As mentioned earlier, Kloiber et al. (2009) report significant correlation between hip extension angular displacement and vertical impact velocity in a jumping front-leg axe-kick.

Table 1. Selection of anthropometric, temporal and kinematic variables investigated. Flexion is positive, extension negative.

Parameter name	Variable	Measure	Comments
Impact Velocity	IV	$m \cdot s^{-1}$	Euclidean norm of velocity vector of the ankle marker (lateral malleolus) at impact
Thigh Length	TL	m	-
Shank Length	SL	m	-
Body Mass	BM	kg	-
Pelvic Tilt Velocity Minimum Timing	TVPmin	%	duration from take-off to instant of occurrence (time normalized)
Hip Flexion Velocity Maximum Timing	TVHmax	%	duration from take-off to instant of occurrence (time normalized)
Knee Flexion Velocity Minimum Timing	TVKmin	%	duration from take-off to instant of occurrence (time normalized)
Pelvic Tilt Velocity Maximum Timing	TVPmax	%	duration from take-off to instant of occurrence (time normalized)
Hip Flexion Velocity Minimum Timing	TVHmin	%	duration from take-off to instant of occurrence (time normalized)
Knee Flexion Velocity Maximum Timing	TVKmax	%	duration from take-off to instant of occurrence (time normalized)
Pelvic Tilt Angle	APT	°	joint angle difference between minimum and at impact
Hip Flexion Angle	AHF	°	joint angle difference between maximum and at impact
Knee Flexion Angle	AKF	°	joint angle difference between minimum and at impact
Pelvic Tilt Velocity	VPT	$° \cdot s^{-1}$	segment angular velocity at impact
Hip Flexion Velocity	VHF	$° \cdot s^{-1}$	joint angular velocity at impact
Knee Flexion Velocity	VKF	$° \cdot s^{-1}$	joint angular velocity at impact

As scientific literature on the jumping front-leg axe kick is sparse, the aim of this study was to record impact velocities (IV) of the jumping front-leg axe-kick and to determine anthropometric, kinematic and temporal parameters that contribute to high impact velocity of the foot and if proximal-to-distal sequencing was prevalent in the techniques. Table 1 depicts the anthropometric, temporal and kinematic parameters that were investigated.

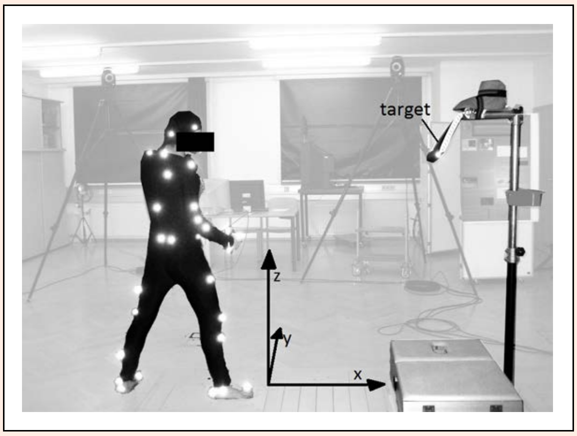

Figure 2. **Test setup: Athlete in fighting stance wearing reflective markers, ready to attack the target. The reference axes are highlighted: x showing in direction of the attack, y in the horizontal plane left to x and z in vertical direction.**

Methods

Participants

A sample of 22 male taekwondo athletes aged from 17 to 43 years (age: 23 ± 5.3 years; body mass: 73 ± 6.4 kg; body height: 1.79 ± 0.06 m; body mass index: 23 ± 1.9 $kg \cdot m^{-2}$) participated in this study. For the time of the study all participants were in physically good condition and reported no injuries or pain. The athletes were of various performance levels. Each of them had at least 4 years of training experience. Within the participants seven athletes had been able to achieve a medal ranking at Austrian National tournaments previous to the investigation. The study was approved by the university's ethics committee and the participants signed informed consent.

Test procedure

First, the athlete's anthropometric measurements required by the Plug-in Gait model were collected. Then kinematic data of a neutral standing position (T-pose) according to the Vicon Plug-in Gait protocol was recorded in order to calculate segment definitions and joint offsets (Vicon®, 2010). Then the participants had to perform a general warm up for a total of 10 minutes, including stretching and light kicking. They started from a fighting stance with the kicking leg closer to the laterally placed target, a marker equipped kicking pad that is common in kicking technique training (PR1614 Hand Mit, Daedo, Barcelona, Spain). The pad was mounted on an aluminium frame at chin height (target height). Its hitting surface was kept in an inclination angle of approximately 60° facing the athlete (see Figure 2). The athletes were allowed to position the target at their comfort distance (Kim et al., 2010). For the recording, each participant was asked to perform five maximum-effort kicks from the initial starting position onto the target. After that the recording was halted and the athlete was asked if he had accustomed to the laboratory situation and felt to have performed well. If this was not the case another five kicks were recorded. The actual total number of kicks varied between 9 and 20, depending on the occurrence of marker dropping during the recording.

Table 2. Anatomical landmarks for marker placement according to the 39-marker Vicon® full-body Plug-In Gait (UPA and FRM) Model.

Segment	Marker Name	Anatomical Location
Head	left front head (LFHD)	left temple
	right front head (RFHD)	right temple
	left back head (LBHD)	left back of head
	right back head (RBHD)	right back of head
	LBHD and RBHD should lie on the head's transversal plane together with the frontal markers.	
Torso	7th cervical vertebra (C7)	spinous process of the 7th cervical vertebra
	10th thoracic vertebra (T10)	spinous process of the 10th thoracic vertebra
	clavicle (CLAV)	jugular notch where clavicles meet the sternum
	sternum (STRN)	xyphoid process of the sternum
	right back (RBAK)	anywhere on the right scapula
Upper Limbs	left/right shoulder (LSHO/RSHO)	acromio-clavicular joint of the left/right shoulder
	left upper arm (LUPA)	upper lateral 1/3 surface of left upper arm (asymetrical to RUPA)
	right upper arm (RUPA)	lower lateral 1/3 surface of right upper arm (asymetrical to LUPA)
	left/right elbow (LELB/RELB)	lateral epicondyle of the left/right arm
	left forearm (LFRM)	lower lateral 1/3 surface of left forearm (asymetrical to RFRM)
	right forearm (RFRM)	upper lateral 1/3 surface of right forearm (asymetrical to LFRM)
	left/right wrist marker A (LWRA/RWRA)	thumb side of a bar attached symmetrically with a wrist-band on the posterior of the left/right wrist as close to the wrist joint centre as possible
Pelvis	left/right wrist marker B (LWRB/RWRB)	little finger side of a bar attached symmetrically with a wristband on the posterior of the left/right wrist as close to the wrist joint centre as possible
	left/right finger (LFIN/RFIN)	proximal to the middle knuckle on the left/right hand
	left/right anterior spina iliaca (LASI/RASI)	left/right anterior superior iliac spine
	left/right posterior spina iliaca (LASI/RASI)	left/right posterior superior iliac spine (below the sacro-iliac joints, where spine joins the pelvis)
Lower Limbs	left thigh (LTHI)	lower lateral 1/3 surface of the left thigh in line with the hip and knee joint centres
	right thigh (RTHI)	upper lateral 1/3 surface of the right thigh in line with the hip and knee joint centres
	left/right knee (LKNE/RKNE)	lateral on the flexion-extension axis of the left/right knee
	left tibia (LTIB)	lower lateral 1/3 surface of the left shank
	right tibia (RTIB)	lower lateral 1/3 surface of the right shank
	left/right ankle (LANK/RANK)	lateral malleolus of the left/right leg
	left/right toe (LTOE/RTOE)	second metatarsal head, midfoot-side of the equinus break between forefoot and midfoot
	left/right heel (LHEE/RHEE)	calcaneus at the same height above the plantar surface of the foot as the toe marker

Kinematic analysis

Kinematic data was recorded using a motion tracking system (Vicon Motion Systems Limited, Oxford, UK) sampling at 250 Hz. The system consisted of eight infra-red cameras (six 1.3 Mega Pixel cameras, and two 4.0 Mega Pixel cameras), an acquisition station system (Vicon MX Net), a personal computer and 3D reconstruction software (Vicon Nexus 1.6.1). 39 reflective markers were attached to specific anatomical landmarks (see Table 2) according to the "Plug-In Gait Full Body (UPA and FRM)" marker set (Vicon®, 2010). After raw data acquisition, the anatomical landmarks were assigned to the trajectories. Data were smoothed using a Woltring filter routine (Woltring, 1986). Using a three dimensional model (Plug-In Gait, Vicon Peak, Oxford, UK) joint centres were located and segment and joint angles and offsets were calculated (Wagner et al., 2010). The kicking leg's ankle marker velocity vectors in the three Cartesian coordinates of all kicks were read out using the Vicon Nexus software. Euclidean norm of the ankle velocity vector was calculated for all kicks at the instant of target contact. The kick with the highest impact velocity (IV) was selected for further processing (Sørensen et al., 1996, Landeo and McIntosh, 2007). A force plate (Kistler 9281B, Winterthur, Switzerland) was used to measure ground reaction forces (at 1000 Hz) in order to determine the instant of loss of contact to the ground at take-off. The temporal and kinematic parameters were read out using Polygon 3.5.1 software (Vicon Peak, Oxford, UK).

Kinematic parameters

Three-dimensional segment angles (Cardan angles) of the pelvis are calculated relative to the global coordinate system. Pelvic tilt is the angle between the sagittal axis of the pelvis and the floor, where positive values of pelvic tilt angle (angular velocity) correspond to an anterior tilt (tilting movement). The hip joint angle is determined by the thigh segment's orientation relative to the pelvis segment. Hip flexion is the angle between the thigh's sagittal axis and the pelvis' transversal plane. Positive hip flexion corresponds to raising the thigh so that the thigh's front moves towards the pelvis' transversal plane - negative hip flexion straightens the thigh again or hyperextends it backwards. Knee joint angles are calculated by the orientation of the shank segment relative to the thigh segment. Knee flexion is the angle between the shanks sagittal axis and the thigh's transversal plane. Positive knee flexion rotates the calves closer towards the hamstrings - bends the knee, negative flexion extends the knee. Positive segment and joint angles are depicted in Figure 1.

Pelvic tilt angle range (APT) and knee flexion angle range (AKF) are determined by the difference between the minimum angle and that at target contact. Hip flexion angle range (AHF) has been defined as the difference between the maximum angle and that at target contact. We investigated pelvic tilt angular segment velocity (VPT), hip flexion angular joint velocity (VHF) and knee flexion angular joint velocity (VKF) at the instant of initial contact of the foot with the target.

Temporal parameters

For determination of proximal-to-distal sequencing the movement was time-normalized between the take-off of the kicking leg (0%) and the instant of initial target contact (100%). The timing of pelvic tilt velocity minimum (TVPmin), hip flexion velocity maximum (TVHmax) and knee flexion velocity minimum (TVKmin) was determined during the lifting motion of the kicking leg. This lifting motion is terminated by the hip angular velocity's directional change from flexion to extension movement at T1 - the curve going from positive to negative (TVPmin, TVHmax, TVKmin < T1). The timing of pelvic tilt velocity maximum (TVPmax), hip flexion velocity minimum (TVHmin) and knee flexion velocity maximum (TVKmax) was determined during the lowering of the leg onto the target (T1 < TVPmax, TVHmin, TVKmax). Proximal-to-distal sequencing was assigned if TVPmin < TVHmax < TVKmin and TVPmax < TVHmin < TVKmax, respectively. For T > T1, if the lowest (highest) value for hip angular velocity (pelvis angular velocity, knee angular velocity) occurred at 100% but hadn't reached its' local extremum yet, we assigned 100% for the timing. Otherwise, an earlier extremum was sought (see Figures 3-5).

Statistical analysis

Statistical analyses were performed using SPSS ver. 22 (IBM Corp., Chicago, Illinois). All variables were tested for normal distribution using a Shapiro-Wilk Test. Mean, median, minima and maxima, and standard deviations were calculated for descriptive statistics. The occurrence of a proximal-to-distal sequencing for the leg-raising period and the leg-lowering period of each analysed kick was determined. Two Chi-Square tests were used to determine if the number of kicks with proximal-to-distal sequencing was significantly greater than 50% (df = 1) - one test for the leg-raising period and one for the leg-lowering period. The relations between the dependent variable (IV) and the independent anthropometric, temporal and kinematic variables were determined using Pearson's correlation coefficient if the data showed normal distribution. Otherwise, Spearman's correlation was used. Significance level was set to p = 0.05. Effect size was determined by the Pearson's (Spearman's) correlation coefficient and is considered to be of practical relevance above r = 0.2 (ρ = 0.2), of moderate effect for r = 0.5 (ρ = 0.5) and strong for r = 0.8 (ρ = 0.8) and above (Cohen 1988, Ferguson 2009). Using the significant correlated normally distributed variables, a forward and a backwards step linear regression analysis was conducted in order to identify the most influential variables. If both procedures result in different predicting models, the one with higher adjusted R2 is selected (Diez et al., 2015).

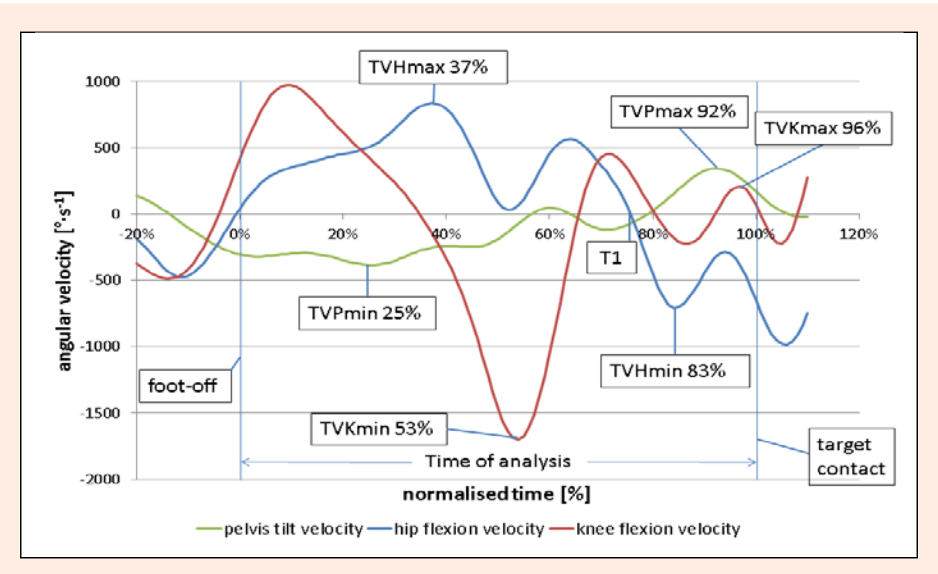

Figure 3. **Diagram of pelvis, hip and knee angular velocities and temporal parameters TVPmin/max, TVHmax/min, TVKmin/max and T1. This technique shows a proximal-to-distal sequencing characteristic for the leg raising period (TVPmin < TVHmax < TVKmin < T1) but no such pattern for the leg lowering period (T1 < TVHmin < TVPmax < TVKmax).**

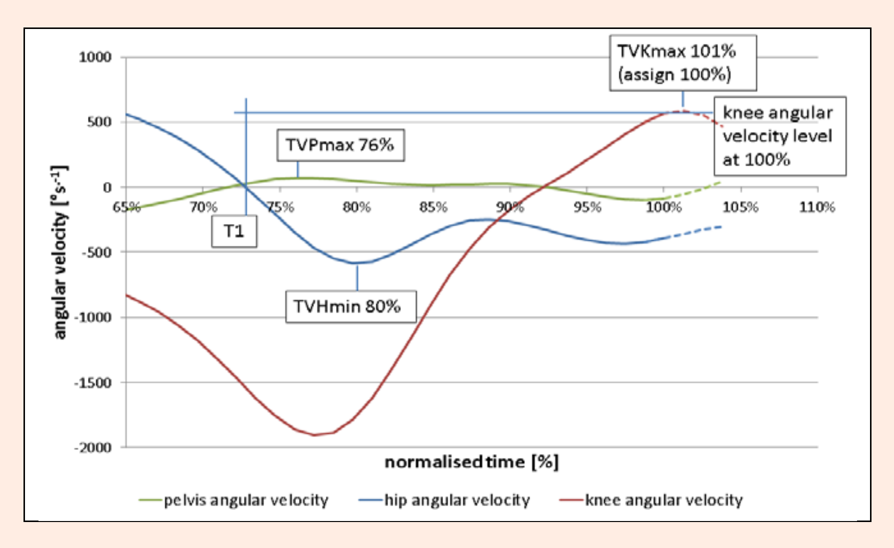

Figure 4. **Diagram of pelvis, hip and knee angular velocities during leg lowering period of a jumping front leg axe-kick. Knee flexion angular velocity meets its maximum at 101% normalized time. As the value at 100% is the maximum within the range [T1, 100%], TVKmax is assigned 100% normalized time. In this case, the technique shows proximal-to-distal sequencing in the leg lowering period.**

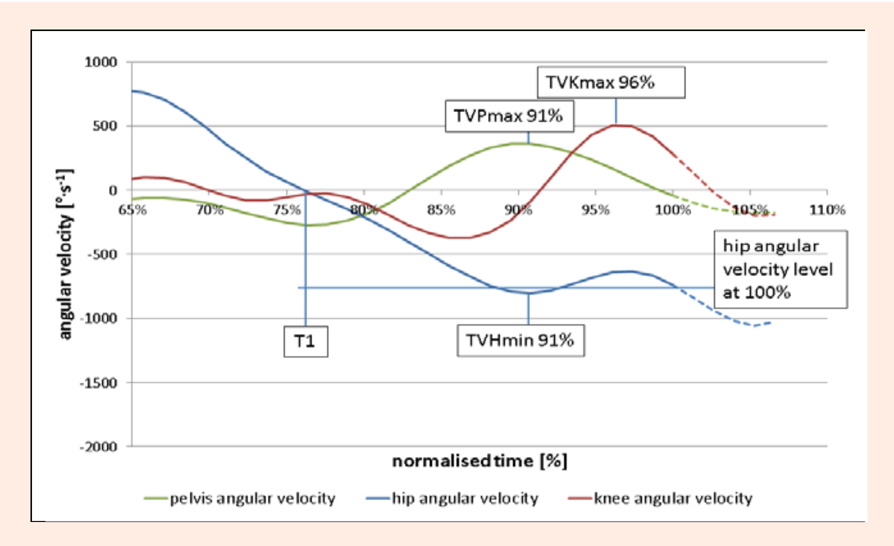

Figure 5. **Diagram of pelvis, hip and knee angular velocities during leg lowering period of a jumping front leg axe-kick. Hip angular velocity has its' minimum at 105% but the level at 100% is not as low as the preceding local minimum. Although extension velocity is much higher after target contact, TVHmin is assigned 91% normalized time. As TVPmax and TVHmin happen at the same time, no proximal-to-distal sequencing is found in this leg lowering period.**

Results

The test for normality shows that the temporal parameters TVHmax, TVPmax, TVHmin, TVKmax and the kinematic parameters AKF, VKF significantly differ from a normal distribution. Descriptive statistics, findings on normality and correlations are presented in Table 3. No significant correlations were found between impact velocity (7.780 ± 0.918 $m \cdot s^{-1}$) and the anthropometric parameters. Significant Pearson correlations of relevant effect were found between impact velocity and the kinematic parameters APT (r = 0.468, *p* = 0.028) and VHF (r = -0.446, *p* = 0.037). Furthermore, our data show significant correlations of relevance between IV and the temporal parameters TVPmin (r = -0.426, *p* = 0.048) and TVKmin (r = -0.480, *p* = 0.024).

The parameters chosen on basis of their significance in the correlation analysis were TVPmin, TVKmin, APT and VHF. Forward step linear regression analysis revealed a model (M1) with only one, the most significant correlated parameter TVKmin and a constant as predictors (adjusted R^2 = 0.192).

*M*1: *IV* = 10.712 – 0.043 *TVKmin*

Backward step linear regression analysis resulted in a different model (M2) of a constant and three predictor variables: VHF, APT and TVPmin. This model achieved a better strength of fit to our data (adjusted R^2 = 0.524) than the forward step model.

*M*2: *IV* = 7.549 + 0.800 *APT* – 0.010 *VHF* – 0.130 *TVPmin*

Table 4 shows the output of the regression analysis for M2. For the period that the kicking leg is lifted, the

Table 3. Descriptive statistics of the investigated variables of the jumping front-foot axe-kick (n = 22). Pearson (r) and Spearman (ρ) correlation coefficients of variables relate to impact velocity.

Variable	Measure	minimum	maximum	mean / median†	s	r / ρ
IV	$m\cdot s^{-1}$	5.9	9.5	7.78	.918	-
TL	m	.38	.47	.42	.025	r = 0.053
SL	m	.38	.47	.42	.025	r = -0.064
BM	kg	63	83	73	6.4	r = 0.182
TVPmin	%	2	87	30.9	23.60	r = -0.426*
TVHmax†	%	34	65	44†	-	ρ = -0.297
TVKmin	%	49	82	67.7	10.15	r = -0.480*
TVPmax†	%	71	100	92.7†	-	ρ = 0.161
TVHmin†	%	63	100	86.6†	-	ρ = 0.294
TVKmax†	%	85	100	99.3†	-	ρ = -0.206
APT	°	-13	19	3.0	6.63	r = 0.468*
AHF	°	-65	-5	-26.0	14.42	r = -0.294
AKF†	°	2	70	15†	-	ρ = -0.028
VPT	$°\cdot s^{-1}$	-74	-343	98.2	114.20	r = 0.220
VHF	$°\cdot s^{-1}$	-713	498	-267.4	272.30	r = -0.446*
VKF†	$°\cdot s^{-1}$	105	1389	447†	-	ρ = -0.256

* $p < 0.05$; † variable is not normally distributed.

Table 4. Partial regression coefficients B, β coefficients, standard error of the mean SEM and significance for estimated variables of M2.

Variable	B	SEM	β	t	sig
constant	7.549	.328		22.986	.000
APT	.080	.021	0.574	3.757	.001
VHF	-.001	.001	-0.419	-2.530	.021
TVPmin	-.013	.006	-0.321	-1.958	.066

timing of TVPmin, TVHmax and TVKmin shows a proximal-to-distal pattern in 15 out of 22 participants. During the leg-lowering period only 9 persons kick with TVPmax, TVHmin and TVKmax in a proximal-to-distal sequence. The Chi-Square tests show no significant results, neither for the leg-raising (χ^2 = 2.909) nor the leg-lowering period (χ^2 = 0.727).

Discussion

Impact velocity

Bercades and Pieter (2006) reviewed literature on taekwondo axe-kicks. Concerning peak linear foot velocity, they cite values ranging up to 10.4 $m\cdot s^{-1}$ for jumping front leg axe-kicks (Sung, 1987) without giving number or level of participants. In Yu et al. (2012) the 4 professional subjects created a maximal speed of ankle during the drive of 10.9 ± 1.2 $m\cdot s^{-1}$ with back leg axe-kicks. Yet it has to be distinguished between maximal speed and speed at the instant of impact, which not necessarily has to be identical. Other studies report considerably lower linear foot velocities at impact. Tsai et al. (2004) and Tsai et al. (2005) report movement velocities of 5.30 ± 0.35 $m\cdot s^{-1}$ and linear velocities of the ankle at impact of 4.64 ± 1.02 $m\cdot s^{-1}$, respectively.

These values are considerably different from our results with a mean impact velocity of 7.78 ± 0.918 $m\cdot s^{-1}$. This may be caused by differences in the task of executing a forceful blow in our case and to deliver an attack of short duration in Tsai et al. (2005). Other reasons that the athletes were able to achieve higher linear impact velocity of the ankle in this study could be a result of the jumping motion or the kind of target that was chosen. Tsai and Huang (2006) found attack velocity on target of 7.74 ± 0.75 $m\cdot s^{-1}$ for straight axe-kick analysing five female and three male athletes from the National Taiwan Normal University taekwondo team. Fife et al. (2010) report peak foot velocities of 8.48 ± 1.86 $m\cdot s^{-1}$ for two male participants kicking against an instrumented head form. Kloiber et al. (2009) report vertical impact velocities of 8 ± 1$m\cdot s^{-1}$ for the best jumping front-leg axe-kicks of 19 male and female Taekwondo athletes, which is consistent with our findings. Jumping front-leg axe-kicks have end-point velocities at impact in the range between the throwlike and the slower pushlike (Kim et al., 2011) kicking movements.

Anthropometric parameters

The chosen anthropometric parameters did not contribute significantly to impact velocity. The segment lengths of both thigh and shank we found for the participating athletes were 0.42 ± 0.025 m. These lengths are consistent with the data of Plagenhoef et al. (1983). From a kinematic perspective the length of the involved segments is likely to play a role in the production of a high linear velocity of the distal end. However, benefits from the longer radius seem to be compromised by an increase of the moment of inertia, which inhibits angular acceleration. For martial art kicks, no studies analysing correlation between segment lengths and impact velocity could be found. In soccer kicks, De Witt and Hinrichs (2012) reported that segment lengths did not correlate with ball velocity. Taking into account that high foot velocity correlates strongly with ball velocity (r = 0.83, $p < 0.01$) we assume that thigh and shank lengths did not contribute to foot velocity either. This would be in accordance to the role of TL and

SL for the production of high IV in the jumping front-leg axe-kick.

We found similar BM for this study's participants (73 ± 6.4 kg) compared to Estevan et al. (2013) with 72.94 ± 16.09 kg who include both male and female athletes. In addition, body mass index lies in a normal range with BMI = 23 ± 1.9 kg·m^{-2} in this study. Considering that an athlete who strikes or kicks a target does not have to accelerate an external mass before impact, the ratio between that external mass and the power-producing body mass does not play a role for reaching high impact velocities. If the impact's transfer of linear momentum is analysed BM is likely to play a role. Congruently, Walilko et al. (2005) report no significant correlation between body mass and hand velocity at impact of boxing punches but found a significant correlation between body mass and punch force (r = 0.539). According to Heller et al. (1998), Taekwondo athletes have low body fat (8.2% of body mass or 62.1% of the norm) and high anaerobic power output (14.7 W·kg-1 or 160% of the norm). We can therefore assume that Taekwondo athletes are not likely to be inhibited by excess body mass in generating high segment velocities. A good power to body mass ratio seems to be of such basic requirement that no effect of body mass on impact velocity could be found in this study. However, we believe that an effect of body mass could be detectable if weight distribution varied in a wider range than it did in the group of this study.

Kinematic parameters

The pelvis tilt angle APT (3.0 ± 6.63°) corresponds to the angular displacement of the pelvis' front towards the floor in direction of the attack. Often, Masters of Asian martial arts stress the importance of starting the movement of kicks and strikes from the pelvis. This teaching seems to get support from our study on the jumping front-leg axe-kick as APT correlates significantly (r = 0.468) with impact velocity. It is also part of the linear regression model M2 and has a positive coefficient. So, does a greater APT lead to higher IV by accelerating the involved segments through a larger acceleration angle? A prerequisite for this is tilting the pelvis backwards beforehand by arching the lower back in kyphosis during the period of raising the leg. This is done by the most participants in this study. Main differences occur from the time the leg is lowered onto the target. As indicated by the descriptive statistics, about half of the athletes kept APT at a minimum angle or even continued to tilt the pelvis backwards, which is counter-directive in the leg-lowering period. As this is done by leaning back the torso, this behaviour helps the athlete to lengthen the distance to a counter-attacking opponent but might compromise efforts to accelerate the kicking leg by hip extension. Moreover, athletes expect a better dynamic balance through a counter-directive movement between torso and kicking leg. We think that rather the backward tilt of the pelvis in the leg-lowering period is detrimental in reaching high IV than a high APT-level is mandatory.

The athletes in our study reached VHF values of -267.4 ± 272.30°·s^{-1}. The assumption, that hip extension is a main propulsive action in the leg-lowering period, is supported by the significant correlation of VHF with IV (r = -0.446). In the M2 model VHF has a negative coefficient. According to M2, maximizing the angular velocity of the hip extension leads to higher IV. Other strategies would be to maximise VPT or to maximise VKF. Although we found a significant correlation for APT, we think that maximising VPT is rather inconvenient as this is achieved by fast contraction of the lower back muscles, leading to high flexion moments in the lower back. This might lead to high pressure in the intervertebral discs. Three of four hamstring muscles that flex the knee are stretched over the hip and knee joint. Contraction of these muscles is therefore inducing hip extension and knee flexion moments. If rotation occurs around the hip or knee axis is therefore depending on which antagonist muscles' contract. Maximising VKF is therefore leading to minimized capacities to reach high extension velocity in the hip. Zajac (1993) even stated that “angular acceleration of the joints spanned by a bi-articular muscle can be opposite to the joint torques it produces.” This might be the case for two athletes who showed counter-acting positive VHF and unusually high values of VKF and VPT, respectively. The radius of the ankle trajectory's curvature diminishes with flexion of the knee, whereas it keeps its length in an exclusive hip extension. So maximising VKF leads to a shorter fighting range. Looking at our results, we think that an athlete considering the trade-off between knee flexion and hip extension velocity through hamstring contraction should rather concentrate on minimizing VHF. In other words, rapid hip extension should be preferred to a rapid knee flexion for high IV in a jumping front-leg axe-kick.

Temporal parameters

The temporal parameters that correlate significantly with impact velocity are TVPmin (r = -0.426) and TVKmin (r = -0.480). Both correlation coefficients have negative values. However, in the backward step linear regression model M2, TVKmin does not contribute to predict IV. The pelvis backwards tilt and the knee extension should be performed early in the leg-raising period. We assume that this promotes the shortening of the leg-raising period in comparison to the leg-lowering period of the technique. By this, the athlete has more time to accelerate his foot in the leg-lowering direction onto the target, therefore reaching higher linear velocity of the ankle.

Proximal-to-distal sequencing

According to Tsai et al. (2005), the kinetic chain principle applies only to the leg-raising period of the front-leg axe-kick, not during the pull-down. Looking at the results from our data, we cannot confirm any of the two findings for the jumping front-leg axe-kick as the analysed kicks show no significant difference from uniform distribution of occurrence and absence of proximal-to-distal sequencing. However, Tsai et al. (2005) analysed the sequencing based on linear velocity magnitudes of the hip, knee and ankle joint of a selected athlete. In contrast, we analysed angular segment and joint velocities of each athlete's best kick in this study. In the presented study, the athletes did not kick onto a rigid target. The kicking pad flexed downwards when hit by the foot, so that the foot was allowed to further accelerate towards the ground. Hence, often the magnitude of linear ankle velocity reached higher levels after target contact than before or at initial target contact, with the maximum approximately when the ankle reached hip height. The same applies for the peaks of hip flexion and knee flexion velocity. Hip flexion reached lower negative values (higher hip extension velocity) and knee flexion higher positive values after target contact than within the analysed period of the technique. Even though the kick is usually used to hit head high targets, its functional optimum for high impact velocity seems to be at hip height. That height does not have any practical relevance in a Taekwondo match. However, using an experimental setup with a hip height target might reveal a proximal-to-distal sequencing for the leg-lowering period. An analysis like that might be useful in the art of board breaking.

Limitations

In this study, a few athletes wore a tight lycra suit (as seen in Figure 2). Reflective markers were attached onto the suit using hook-and-pile fasteners. Compared to the trials with the markers directly applied on skin additional errors may be expected. In order to assess this error we investigated the segmental lengths of the calculated femur segments of two fighters during one series of kicks. Results showed a coefficient of variance of 0.018 for the femur length without suit compared to 0.034 of the person wearing a suit. From this, it may be concluded that the kinematic data obtained for the athletes wearing the suit are less accurate than those having the markers attached to the skin.

Conclusion

Examining the jumping front-leg axe-kick we found higher impact velocities of the ankle compared to Tsai et al. (2005) for the front-leg axe-kick and consistent values with Kloiber et al. (2009) who also investigated jumping front-leg axe-kicks. The kinematic parameters that correlated significantly with IV were APT and VHF. The positive correlation of APT supports an attacking behaviour with an upright torso rather than leaning back during the leg-lowering period if high IV is needed and no counterattack is expected, like in board breaking. The significant negative correlation of VHF and IV points to the importance of reaching a high extension velocity of the hip. As there is no significant correlation of IV with VKF, we propose that athletes should concentrate on hip extension in the leg-lowering period rather than knee flexion. Athletes, who were able to reach early TVPmin and TVKmin peaks, accomplished the task of raising the leg earlier and therefore had more time to accelerate the involved segments in the actual attacking direction. In contrast to Tsai et al. (2005), we couldn't find statistical evidence for proximal-to-distal sequencing by the characteristics of pelvis tilt, hip and knee flexion velocities, neither for the leg-raising nor the leg-lowering period.

Acknowledgements

This study was not funded. The authors would like to thank the individuals participating in this study. The experiments described complied with the Austrian federal law and were approved by the ethics committee of the University of Vienna.

References

Ahn, J.D., Hong, S.H. and Park, Y.K. (2009) The historical and cultural identity of Taekwondo as a traditional Korean martial art. *The International Journal of the History of Sport* **26(11),** 1716-1734.

Bercades, L.T. and Pieter, W. (2006) A biomechanical analysis of the modified Taekwondo axe kick. *Journal of Asian Martial Arts* **15(4),** 8-19.

Blum, H. (1977) Physics and the art of kicking and punching. *American Journal of Physics* **45(1),** 61-64.

Cohen, J. (1988) *Statistical power analysis for the behavioral sciences.* 2nd edition. Lawrence Erlbaum Associates, Hillsdale, NJ.

De Witt, J.K. and Hinrichs, R.N. (2012) Mechanical factors associated with the development of high ball velocity during an instep soccer kick. *Sports Biomechanics* **11(3),** 382-390.

Diez, D.M., Barr, C.D. and Çetinkaya-Rundel, M. (2015) *OpenIntro Statistics.* Third Edition. Updated October 18th, 2015. Available form URL: https://drive.google.com/file/d/0B-DHaDEbiOGkUlJIbEhkY05ub2c/view?pli=1

Estevan, I., Jandacka, D. and Coral, F. (2013) Effect of stance position on kick performance in taekwondo. *Journal of Sport Science* **31(16),** 1815-1822.

Falco, C., Alvarez, O., Castillo, I., Estevan, I., Martos, J., Mugarro, F. and Iradi, A. (2009) Influence of the distance in a roundhouse kick's execution time and impact force in Taekwondo. *Journal of Biomechanics* **42,** 242-248.

Ferguson, C.J. (2009) An Effect Size Primer: A Guide for Clinicians and Researchers. *Professional Psychology: Research and Practice* **40(5),** 532-538.

Fife, G.P., Kaminski, T.W., O'Sullivan, D., Pieter, W., Shin, I. and Lim, T. (2010) Velocity of the Taekwondo axe-kick and resultant linear acceleration of an instrumented head form. In: *Conference Proceedings of the Annual Meeting of the American Society of Biomechanics 2010*. Brown University, Providence, RI. 773.

Gulledge, K. J. and Dapena, J. (2008) A comparison of the reverse and power punches in oriental martial arts. *Journal of Sports Sciences* **26(2),** 189-196.

Heller, J., Peric, T., Dlouha, R., Kohlikova, E., Melichna, J. and Novakova, H. (1998) Physiological profiles of male and female taekwon-do (ITF) black belts. *Journal of Sports Sciences* **16(3),** 243-249.

Kazemi, M., Waalen, J., Morgan, C. and White, A.R. (2006) A profile of Olympic Taekwondo competitors. *Journal of Sports Science and Medicine* **5(CSSI 1),** 114-121.

Kellis, E. and Katis, A. (2007) Biomechanical characteristics and determinants of instep soccer kick. *Journal of Sports Science and Medicine* **6,** 154-165.

Khanna, G.L. and Manna, I. (2006).Study of physiological profile of Indian boxers. *Journal of Sport Science and Medicine* **5,** 90-98.

Kim, J.W., Kwon, M.S., Yenuga, S.S. and Kwon, Y.H. (2010) The effects of target distance on pivot hip, trunk, pelvis and kicking leg kinematics in Taekwondo roundhouse kicks. *Sports Biomechanics* **9(2),** 98-114.

Kim, Y.K., Kim, Y.H. and Im, S.J. (2011) Inter-joint coordination in producing kicking velocity of Taekwondo kicks. *Journal of Sports Science and Medicine* **10,** 31-38.

Kloiber, M., Baca, A., Preuschl, E. and Horsak, B. (2009) A kinematic analysis of the naeryo-chagi technique in taekwondo. In: *Proceedings of the 27th International Symposium on Biomechanics in Sports.* Eds: Harrison, A. J., Anderson, R. and Kenny, I. Limerick, Ireland: University of Limerick. 404-407.

Landeo, R. and McIntosh, S.A. (2007) Fast front kick: Gaining insights beyond the data. In: *Proceedings of the 25th International Symposium on Biomechanics in Sports.* Eds: Menzel, H.J. and Chagas, M.H. Ouro Preto: Brazil. 293-296.

Levanon, J. and Dapena, J. (1998) Comparison of the kinematics of the full-instep and pass kicks in soccer. *Medicine and Science in Sports and Exercise* **30,** 917-927.

Matsushigue, K., Hartmann, K. and Franchini, E. (2009) Taekwondo: Physiological responses and match analysis. *Journal of Strength and Conditioning Research* **23,** 1112–1117.

Menescardi, C., Lopez-Lopez, J.A., Falco, C., Hernandez-Mendo, A. and Estevan, I. (2015) Tactical aspects of a National university Taekwondo championship in relation to round and match outcome. *Journal of Strength and Conditioning Research* **29(2),** 466-471.

Nunome, H., Asai, T., Ikegami, Y. and Sakurai, S. (2002) Three dimensional kinetic analysis of side-foot and instep soccer kicks. *Medicine and Science in Sports and Exercise* **34,** 2028-2036.

O'Sullivan, D., Chung, Ch., Lee, K., Kim, E., Kang, S., Kim, T. and Shin, I. (2009) Measurement and comparison of Taekwondo and Yongmudo turning kick impact force for two target heights. *Journal of Sports Science and Medicine* **8(CSSI 3),** 13-16.

Park, Y. (1999). Taekwondo. The ultimate reference guide to the world's most popular martial art. Facts on file, Inc., New York.

Pearson, J.N. (1997) *Kinematics and kinetics of the taekwondo turning kick.* Bachelor's thesis, University of Otago, Dunedin, New Zealand.

Plagenhoef, S., Evans, F.G. and Abdelnour, T. (1983) Anatomical data for analyzing human motion. *Research Quarterly for Exercise and Sport* **54,** 169-178.

Preuschl, E. and Attarpour, G. (2014) Biomechanik und Bewegungsanalysen von Kampfsport-Kicktechniken: Schwerpunkt Taekwondo. New academic press, Budapest.

Putnam, C.A. (1993) Sequential motions of body segments in striking and throwing skills: Descriptions and explanations. *Journal of Biomechanics* **26(Suppl. 1),** 125-135.

Smith, M.S. (2006) Physiological profile of senior and junior England International amateur boxers. *Journal of Sports Science and Medicine* **5(CSSI 1),** 74-89.

Sørensen H., Zachoi, M. Simonsen, E.B. Dyhre-Poulsen, P. and Klausen, K. (1996) Dynamics of the martial arts high front kick. *Journal of Sports Sciences* **14,** 483-495.

Streif, G. (1993) *Taekwondo Modern.* Sport-Buch-Verlag H. Velte, Wehrheim, Germany.

Sung, T.Y. (1987) A biomechanical analysis of selected taekwondo kicks. *The Joumal of Taekwondo* **61,**106-115.

Tsai, Y.J., Lee, S.P. and Huang, C. (2004) The biomechanical analysis of taekwondo axe-kick in senior high-school athletic. In: *Proceedings of the 22nd International Symposium on Biomechanics in Sports 2004.* Eds: Lamontagne, M., Gordon, D., Robertson, E., Sveistrup, H. Ottawa, Canada: University of Ottawa. 453-456.

Tsai, Y.J., Gu, G.H., Lee, Ch.J., Huang, Ch.F. and Tsai, Ch.L. (2005) The biomechanical analysis of the taekwondo front-leg axe-kick. In: *Proceedings of the 23rd International Symposium on Biomechanics in Sports 2005*. Ed: Wang, Ch. Beijing, China: China Institute of Sport Science. 437-440.

Tsai, Y.J. and Huang, C.F. (2006) Kinematic analysis of the Taekwondo flex-stretching and straight axe-kick. Abstract from Journal of Physical Education in Higher Education. Available from URL: http://tao.wordpedia.com/show_pdf.ashx?sess=gavp3mblqqdm ojb5miajucfg&file_name=JO00000371_25_81-90&file_type=r

Van den Tillaar, R. and Ettema, G. (2007) A three-dimensional analysis of overarm throwing in experienced handball players. *Journal of Applied Biomechanics* **23,** 12-19.

Vicon® (2010). Plug-in Gait Product Guide - Foundation Notes. Vicon® Motion Systems Ltd., Oxford Metrics Group, Oxford, UK.

Wagner, H., Buchecker, M., von Duvillard, S.P. and Müller, E. (2010) Kinematic description of elite vs. low level players in team-handball jump throw. *Journal of Sports Science and Medicine* **9,** 15-23.

Walilko, T.J., Viano, D.C. and Bir, C.A. (2005) Biomechanics of the head for Olympic boxer punches to the face. *British Journal of Sports Medicine* **39,** 710-719.

Woltring, H.J. (1986) A Fortran package for generalized, cross-validatory spline smoothing and differentiation. *Advances in Engineering Software* **8(2),** 104-113.

World Taekwondo Federation. (2015) Competition rules & interpretation - In force as of May 11th, 2015. Available from URL: http://www.worldtaekwondofederation.net/images/WTF_Competition_Rules__Interpretation_May_11_2015.pdf

Yu, D., Yu, Y., Wilde, B. and Shan, G. (2012) Biomechanical characteristics of the axe kick in Tae Kwon-Do. *Archives of Budo. Science of martial arts* **8(4),** 213-218.

Zajac, F.E., Neptune, R.R. Kautz, S.A. (2002) Biomechanics and muscle coordination of human walking: Part I: Introduction to concepts, power transfer, dynamics and simulations. *Gait & Posture* **16(3),** 215-232.

Key points

- Angular velocity characteristics of the pelvis segment and the kicking leg's hip and knee joint show no proximal-to-distal sequencing, neither for the leg-raising or leg-lowering period in a jumping front-leg axe-kick.
- Anthropometric parameters of taekwondo athlete's do not influence their impact velocities.
- In order to raise the impact velocity in the jumping front-leg axe-kick an athlete should avoid tilting back with the torso. Instead, an upright position should be maintained.
- In the leg-lowering period, we suggest hitting the target by using hip extension with a rather straight knee, instead of flexing the knee.

AUTHOR BIOGRAPHY

Emanuel PREUSCHL

Employment

Project employee; University of Vienna, Institute of Sport Science, Department of Biomechanics, Kinesiology and Applied Computer Science

Degree

Graduate engineer

Research interests

Biomechanics, sports equipment engineering

E-mail: emanuel.preuschl@univie.ac.at

Michaela HASSMANN

Employment

Research assistant; University of Vienna, Institute of Sport Science, Department of Biomechanics, Kinesiology and Applied Computer Science

Degree

MSc

Research interests

Biomechanics, motion analysis

E-mail: michaela.hassmann@univie.ac.at

Arnold BACA

Employment

Professor; University of Vienna, Institute of Sport Science, Department of Biomechanics, Kinesiology and Applied Computer Science

Degree

PhD

Research interests

Computer Science in Sports, Biomechanics

E-mail: arnold.baca@univie.ac.at

✉ **Emanuel Preuschl**

University of Vienna, Institute of Sport Science, Department of Biomechanics, Kinesiology and Applied Computer Science, Auf der Schmelz 6a, 1150 Vienna, Austria.