

Original Research

Effects of Backstep Footwork Patterns on Taekwondo Athletes'

Ground Reaction Forces and Leg Stiffness

Taewoon Jung ¹, Hyungjin Park ^{2,*}¹ Department of Special Physical Education, Yongin University, Yongin, South Korea;
twj3078@hanmail.net² Sport & Health Science Research Institute, Kyungsoo University, Busan, South Korea;
hjpark79@ks.ac.kr* Correspondence: (HP) hjpark79@ks.ac.kr  ORCID ID n° 0000-0002-1165-5809

Received: 11/11/2024; Accepted: 27/04/2025; Published: 30/06/2025

Abstract: This study investigated biomechanical characteristics of defensive footwork patterns during Taekwondo roundhouse kicks, focusing specifically on ground reaction forces (GRF) and leg stiffness properties. Ten elite male Taekwondo practitioners executed roundhouse kicks under various footwork conditions, including angle-based variations ranging from 0° to 90° relative to the transverse axis and distance-based variations incorporating different stepping patterns. Using motion capture and force plate data, we analyzed the relationships between footwork patterns, GRF, and leg stiffness characteristics. Our findings revealed systematic relationships between backstep angle and leg biomechanics. Leg stiffness decreased significantly as backstep angle increased, ranging from 7.0 kN/m at 0° to 4.3 kN/m at 90°. Contact time and impulse showed corresponding increases with larger backstep angles. While distance variations did not significantly affect leg stiffness, they notably influenced impulse characteristics and center of mass displacement. These results provide new insights into the mechanical principles underlying effective defensive movement and counterattack execution in Taekwondo, with implications for technique optimization and training methods.

Keywords: biomechanics; ground reaction force; leg stiffness; martial arts; combat sports



1. Introduction

The biomechanical analysis of defensive movement patterns in combat sports has become increasingly important as competition strategies evolve. In Taekwondo, this evolution is particularly evident in the execution of the roundhouse kick, which comprises more than half of all scoring techniques in elite matches (Koh & Watkinson, 2002; Estevan et al., 2011). Recent rule modifications, particularly the introduction of additional points for head kicks, have intensified the focus on effective defensive movement patterns that enable both evasion and powerful counterattacks (Menescardi et al., 2015; Huang et al., 2022). Contemporary research has highlighted the need for deeper analysis of the biomechanical properties underlying these defensive-offensive transitions, particularly in relation to ground reaction forces and leg stiffness (Preuschl et al., 2016; Camomilla et al., 2020).

The Taekwondo roundhouse kick involves a complex sequence of movements integrating both offensive and defensive elements. This sequence begins with knee chamber position, followed by hip rotation and explosive knee extension, culminating in impact with the target area using the instep (Falco et al., 2009; Kim et al., 2010). Throughout this sequence, the supporting leg plays a crucial role in both stabilization and force generation through its interaction with the ground (Kong et al., 2000; Oh & Choi, 2004).

While previous biomechanical analyses have focused primarily on temporal parameters, impact forces, and joint kinematics of kicking techniques (Shin & Choi, 2001; Gavagan & Sayers, 2017), the

mechanical interaction between the athlete and the ground during different footwork patterns remains largely unexplored. This gap in understanding is particularly significant given that ground reaction forces (GRF) provide crucial insights into force generation and transfer during kick execution. Recent studies by Huang et al. (2022) and Camomilla et al. (2020) have emphasized the importance of support leg mechanics in kick efficiency, suggesting that ground reaction forces significantly influence both stability and power generation capacity during dynamic combat movements.

The concept of leg stiffness, which describes how the leg functions as a spring-mass system during dynamic movements, has proven invaluable in understanding human locomotion (McMahon & Cheng, 1990; Farley et al., 1998). This mechanical property provides insights into both performance optimization and injury prevention across various athletic activities (Farley & Gonzalez, 1996; Seyfarth et al., 1999). However, the modulation of leg stiffness during Taekwondo roundhouse kicks, particularly in defensive scenarios requiring rapid transitions between retreat and attack, remains poorly understood.

Defensive scenarios in Taekwondo competition typically manifest in two main patterns: single-leg backwards steps at various angles and double-leg retreating movements at different distances (Estevan et al., 2011; Huang et al., 2022). The single-leg backwards step involves rapid withdrawal of one foot while maintaining balance on the supporting leg, with the athlete pivoting at various angles (0° - 90°) relative to the original stance position. This movement primarily facilitates evasion while maintaining

proximity for counterattacks. In contrast, the double-leg retreating movement involves sequential or simultaneous movement of both feet, creating greater distance from the opponent while potentially sacrificing counterattack speed (Moenig, 2017; Park et al., 2019). Each pattern imposes unique demands on the neuromuscular system, affecting both GRF and leg stiffness characteristics. Leg stiffness, representing the resistance of the leg to compression during loading, is particularly relevant as it influences both stability during defensive movements and power generation during subsequent attacks (Gavagan & Sayers, 2017). The ability to maintain effective force production while executing these defensive movements represents a crucial aspect of competitive performance, yet the underlying mechanical relationships remain unclear.

The integration of defensive footwork with offensive techniques presents unique biomechanical challenges. The transition from a defensive step to a Taekwondo roundhouse kick requires precise control of center of mass movement and rapid modulation of leg stiffness. Understanding these mechanical relationships is crucial for several reasons:

It could provide insights into optimizing the trade-off between defensive effectiveness and counterattack power

It may help identify more efficient movement strategies for different competitive scenarios

It could inform the development of more targeted training methods

It may contribute to injury prevention by identifying potentially harmful movement patterns

This investigation aimed to examine the characteristics of GRF during Taekwondo roundhouse kicks performed with different footwork strategies and analyze the relationship between footwork variations and leg stiffness properties. Additionally, we sought to understand the implications of these mechanical parameters for kick execution and performance. We hypothesized that:

- GRF parameters would demonstrate systematic changes with varying footwork conditions
- Leg stiffness would show angle-dependent adaptations
- Distance variations would affect loading patterns differently than angular variations
- These findings could enhance our understanding of the biomechanical principles underlying effective Taekwondo performance and inform training methodologies for both coaches and practitioners.

2. Materials and Methods

Subjects — Ten male collegiate Taekwondo athletes participated in this study. The mean body mass, height, age, and training experience of the participants were 60.6 ± 3.7 kg (54.9 to 66.7 kg), 173.1 ± 4.3 cm (167 to 179 cm), 21.7 ± 0.5 years (21 to 22 years), and 8.9 ± 1.1 years (7 to 10 years), respectively. Sample size analysis using G*Power indicated that 15 participants would be needed to achieve a statistical power of 0.80 ($\alpha = 0.05$, effect size $f = 0.45$, correlation = 0.5), suggesting our sample size may be underpowered. Only volunteers who had no serious muscular or joint/ligament problems within six months prior to testing

were included. All participants were right-leg dominant, which was confirmed through their preferred kicking leg in competition. The institutional review board approved all procedures (IRB No. YIU07DOC19), and participants provided informed written consent before testing commenced.

Design— This study employed an observational research approach to analyze ground reaction forces and leg stiffness during defensive footwork patterns in Taekwondo roundhouse kicks. Ten elite male Taekwondo practitioners performed kicks under various footwork conditions, while biomechanical parameters were measured and analyzed without experimental manipulation or intervention.

Methodology— Instrumentation
Motion analysis was conducted using a seven-camera Vicon MX-13 system (Vicon Ltd., Oxford, UK) operating at 250 Hz to track the center of mass movement and leg position for stiffness calculations. Two force platforms (AMTI Inc., BP400600 and BP600900) were used to measure GRF at a sampling frequency of 1000 Hz. The laboratory coordinate system was established with the kicking direction aligned with the anteroposterior (Y) axis, vertical direction with the longitudinal (Z) axis, and mediolateral direction with the transverse (X) axis. The force platforms were time-synchronized with the motion capture system through a manual trigger system that initiated data collection for both systems simultaneously. Impact force measurement utilized a standardized kicking target (All-Star®, Tae Hwa Sports, Seoul, Korea) held at waist height by a trained assistant.

Experimental Protocol - Prior to data collection, participants engaged in a

standardized warm-up protocol consisting of 10 minutes of light jogging, dynamic stretching, and practice kicks. Given that all participants were right-leg dominant, testing standardized the left leg as support and right leg as the striking limb. Target height was normalized to each participant's waist level, with slight downward inclination ($5^\circ \pm 1^\circ$) to optimize impact mechanics.

The testing protocol examined Taekwondo roundhouse kicks under seven distinct conditions, differentiated by defensive footwork patterns. Angular variations included a baseline condition of direct kicks without preliminary footwork, followed by backstep conditions at angles of 0° , 22° , 45° , 67° , and 90° relative to the transverse axis.

Leg stiffness measurements were assessed during the ground contact phase of the backstep movement. Based on the spring-mass model proposed by Seyfarth et al. (1999), leg stiffness was calculated as the ratio of maximum ground reaction force to maximum leg length change. Data collection began at the initial foot contact with the force platform (when vertical GRF exceeded 10N) and continued throughout the stance phase until the foot left the ground or reached stability before kick initiation. Leg length was defined as the distance from the center of mass to the toe marker during this contact phase.

Distance variations were based on each participant's preferred distance (PD), which was determined through a standardized protocol prior to testing. Each participant performed five practice roundhouse kicks at self-selected distances while targeting the standard kicking pad. The average distance between the supporting foot and the target

during these trials was calculated and designated as the participant's preferred distance (PD). Experimental conditions then included the preferred distance itself, short distance ($0.7 \times \text{PD}$), long distance ($1.3 \times \text{PD}$), short distance double-step (DS), and short distance double-cross-step (CS).

The backstep execution began with participants in a standard fighting stance, with body weight evenly distributed between both feet. When performing the defensive footwork, participants coordinated a rapid backward movement of their right foot while simultaneously flexing both knees to maintain a lowered center of mass. Throughout this movement, they maintained a slightly forward-oriented upper body position to enable an efficient transition into the subsequent counterattack. Each condition consisted of five successful trials, with standardized two-minute recovery periods between each trial. A trial was deemed successful if the participant maintained proper form throughout the entire movement sequence, struck the target with the correct striking surface, performed the kick with maximum effort, and completed the movement within the designated force platform area.

Data Processing - Force platform data were filtered using a fourth-order Butterworth low-pass filter with a 50 Hz cutoff frequency. Ground reaction forces were normalized to body weight, and contact time was defined as the duration of foot contact with the force platform during the stepping phase. Leg stiffness was calculated using Seyfarth et al.'s (2002) spring-mass model. The leg length (r) was defined as the distance from the center of mass to the toe marker. The initial leg length (r_0) and final leg

length at impact (r_e) were typically different, with their difference defined as the length parameter r_+ :

$$r_+ = r_e - r_0 \quad \text{Equation (1)}$$

The actual elongated leg length $l(\alpha)$ during ground contact was defined by linear approximation:

$$l(\alpha) = r_0 + r_+ \frac{(\alpha - \alpha_0)}{(\alpha_e - \alpha_0)} = r_0 + \varepsilon(\alpha - \alpha_0) \quad \text{Equation (2)}$$

Where ε represents the leg lengthening constant, α_0 is the leg angle at the kicking event, defined as the moment the kicking foot toe leaves the ground, and α_e is the leg angle at impact, which is the point when the marking on the target mitt begins to move.

$$\Delta r(t) = l(\alpha(t)) - r(t) \quad \text{Equation (3)}$$

Leg stiffness (k) was then defined as the ratio of maximum ground reaction force to maximum leg length change:

$$k = \frac{F_{G.MAX}}{\Delta L} \quad \text{Equation (4)}$$

where $F_{G.MAX}$ is the peak vertical ground reaction force, and ΔL is the leg length change. ΔL was calculated as:

$$\Delta L = \Delta y + L_0(1 - \cos\theta) \quad \text{Equation (5)}$$

where L_0 is the initial length from the ground to the center of mass in standing position, and θ is the angle between the leg and the ground, calculated as:

$$\theta = \sin^{-1}\left(\frac{ut_c}{2L_0}\right) \quad \text{Equation (6)}$$

where u is the horizontal velocity of the center of mass and t_c is the ground contact time.

Statistical Analysis — One-way repeated measures ANOVA was used to compare dependent variables (contact time, GRF, impulse, and leg stiffness) across footwork conditions. When significant main effects were found, post-hoc comparisons were conducted using Bonferroni adjustment for multiple comparisons. Effect sizes were

calculated using partial eta squared (η^2). Statistical significance was set at $p < .05$ for all analyses. All statistical procedures were

performed using SPSS version 24.0 (IBM Corp., Armonk, NY, USA)

Figure 1. Angular variations in backstep footwork patterns. Illustrations showing the five different angles (0° , 22° , 45° , 67° , and 90°) relative to the transverse axis

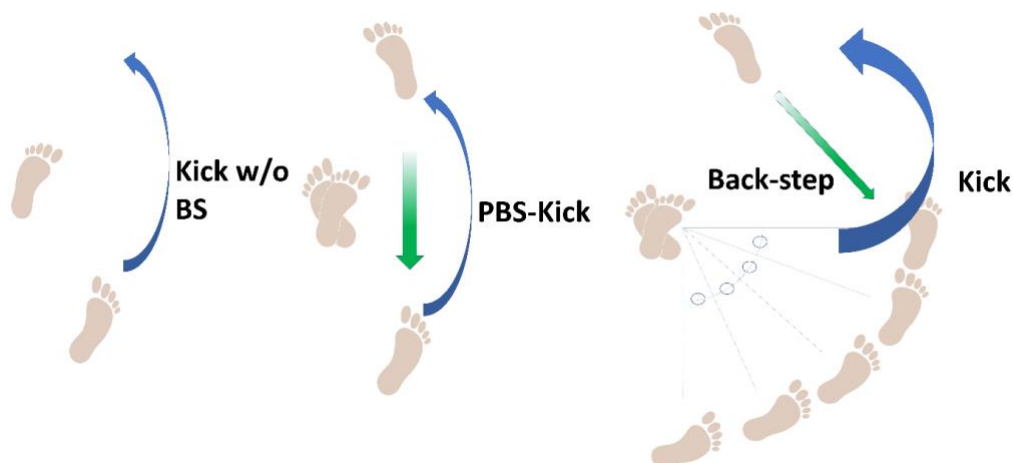
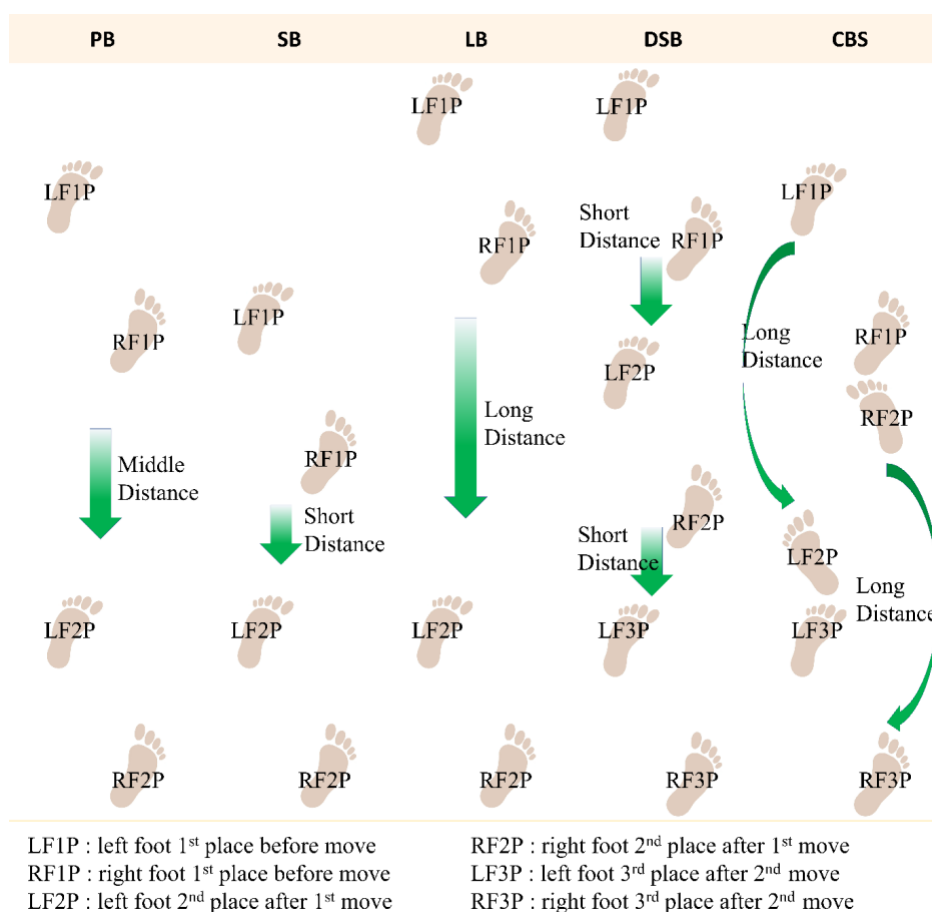


Figure 2. Distance variations in backstep footwork patterns. Illustrations showing the different step distances and patterns: single-step variations including PB (Preferred Backstep - jumping backstep at athlete's preferred distance), SB (Short Backstep - 70% of preferred distance), LB (Long Backstep - 130% of preferred distance); and two-step variations including DSB (Double Short Backstep - consecutive two short backsteps), and CBS (Cross Backstep - first pull back the front left foot (cross), then pull back the front right foot).



3. Results

Ground Reaction Forces and Impulse Parameters - Analysis of the baseline condition (Kick W/O BS) revealed contact time of 0.19 seconds (SD = 0.07), with participants generating a normalized peak vertical GRF of 133.6N (SD = 43.0) and producing an impulse of 92.4N·s (SD = 54.5).

Angular Variations - Analysis revealed significant differences in contact time across angular conditions ($F = 5.544$, $p < .001$). Contact duration increased systematically with angle, beginning at 0.15 seconds (SD = 0.05) for the 0° condition and progressively increasing through 22° ($M = 0.18$ s, $SD = 0.08$), 45° ($M = 0.20$ s, $SD = 0.08$), and 67° ($M = 0.25$ s, $SD = 0.08$), reaching 0.30 seconds (SD = 0.08) at 90°. The preferred back-step (PBS) condition demonstrated an intermediate contact time of 0.26 seconds (SD = 0.08).

While normalized peak vertical GRF showed an increasing trend from 0° ($M = 187.7$ N, $SD = 36.4$) to 90° ($M = 226.6$ N, $SD = 61.2$), these differences did not reach statistical significance ($F = 1.036$, $p = .406$). However, total impulse demonstrated significant variations across angles ($F = 9.819$, $p < .001$), with values progressively increasing from 99.3N·s (SD = 24.4) at 0° to 217.9N·s (SD = 49.8) at 90°.

Distance Variations - Analysis of distance-based variations revealed significant differences in contact times ($F = 3.924$, $p < .01$) across the different conditions. The short distance (SB) condition exhibited the briefest contact time at 0.22 seconds (SD = 0.05), while the long distance (LB) showed 0.34 seconds (SD = 0.07). The preferred distance (PB) and cross-back-step (CBS) conditions showed contact times of 0.28 seconds (SD = 0.06).

Leg Stiffness Characteristics - Supporting leg exhibited significant differences in normalized maximum vertical GRF across angles ($F = 4.088$, $p < .01$). Vertical displacement (Δr) showed significant variations ($F = 7.908$, $p < .001$), increasing systematically from 0.11m (SD = 0.02) at 0° to

0.15m (SD = 0.03) at both 67° and 90° conditions.

The leg lengthening constant (ϵ) demonstrated a significant decreasing trend with increasing angle ($F = 6.623$, $p < .001$). Values decreased from 22.9mm/deg (SD = 9.4) at 0° to 10.4mm/deg (SD = 3.2) at 90°, with the PBS condition showing an intermediate value of 13.5mm/deg (SD = 3.6). Similarly, leg stiffness values displayed significant differences across angles ($F = 9.354$, $p < .001$), decreasing from 7.0kN/m (SD = 1.6) at 0° to 4.3kN/m (SD = 1.5) at 90°.

In contrast to the angle-based variations, distance-based variations showed no significant differences in normalized maximum vertical GRF ($F = 0.487$, $p = .745$) or leg stiffness values ($F = 1.503$, $p = .217$). However, significant differences were observed in angle changes ($F = 10.226$, $p < .001$) and leg lengthening constant ($F = 5.447$, $p < .001$) across distance variations. Post-hoc analyses revealed that the short distance (SB) condition differed significantly from the long distance cross (CBS) in terms of angle changes ($p < .05$), while the double-short-back (DSB) showed significant differences from the short distance (SB) in leg lengthening constant ($p < .05$). These findings suggest that angular variations in defensive movements have a more pronounced effect on leg stiffness characteristics than distance variations. The observed leg stiffness values (ranging from 4.3 to 7.0 kN/m) were notably lower than those previously reported for running and jumping activities (Farley & Gonzalez, 1996; Seyfarth et al., 2002), indicating the unique biomechanical demands of Taekwondo kicking techniques.

Table 1. Ground Reaction Force and Impulse in Angle Variation Types

	Contact Time (s)	Normalized peak vertical GRF (N)	Impulse (N.sec)
Kick W/O BS	0.19±0.07	133.6±43.0	92.4±54.5
PBS Kick#a	0.26±0.08	225.3±59.1	206.7±41.2
0#b	0.15±0.05	187.7±36.4	99.3#a±24.4
22#c	0.18±0.08	198.1±58.3	126.8±38.1
45#d	0.20±0.08	225.3±71.8	162.4±43.2
67#e	0.25±0.08	230.4±39.6	196.6#b±37.0
90#f	0.30#b,c±0.08	226.6±61.2	217.9#b,c,d±49.8
f	5.544	1.036	9.819
sig.	.000***	.406	.000***

Note. GRF = Ground Reaction Force; W/O BS = Without Backstep; PBS = Preferred Backstep; Numbers (0, 22, 45, 67, 90) indicate backstep angles in degrees relative to the transverse axis. Superscript letters (a, b, c, etc.) denote significant differences between the corresponding types at $p < .05$. *** $p < .001$.

Table 2. Ground Reaction Force and Impulse in Distance Variation Types

	Contact Time (s)	Normalized peak vertical GRF (N)	Impulse (N . sec)
PB#a	0.28±0.09	217.1±49.4	230.8±52.1
LB#b	0.34±0.07	203.4±53.3	212.6±32.4
CBS#c	0.28±0.06	224.1±62.4	245.6±47.0
SB#d	0.22±0.05	228.6±53.1	166.3±56.3
DSB#e	0.32#11±0.10	221.5±52.9	257.8#d±51.0
f	3.924	.316	3.117
sig.	.008**	.866	.024*

Note. GRF = Ground Reaction Force; PB = Preferred Backstep; LB = Long Backstep; CBS = Cross Backstep; SB = Short Backstep; DSB = Double Short Backstep. Superscript letters denote significant differences between the corresponding types at $p < .05$. * $p < .05$. ** $p < .01$.

Table 3. Ground Reaction Force and Stiffness in Angle Variation Types

	Normalized peak vertical GRF (N)	Δr (m)	$\Delta \alpha$ (deg)	ϵ (mm/deg)	k (kN/m)
Kick W/O BS	117.3±10.3	0.13±0.02	13.6±2.1	9.5±1.3	5.6±1.2
PBS Kick#a	116.2±13.9	0.15±0.02	12.1±2.8	13.5±3.6	4.5±0.5
0#b	123.0±5.7	0.11#a±0.02	5.3#a±1.9	22.9#2±9.4	7.0#a±1.6
22#c	122.6±18.2	0.12±0.01	7.0#a±2.5	20.0±8.1	5.9±0.9
45#d	124.6±12.3	0.14#b±0.02	11.1#b±2.5	13.6#b±4.2	5.3#b±0.9
67#e	109.0±19.3	0.15#b±0.01	12.9#b,c±3.5	12.5#b±4.3	4.3#b±0.7
90#f	101.1#d±14.3	0.15#b±0.03	14.8#b,c±3.3	10.4#b,c±3.2	4.3#b±1.5
f	4.088	7.908	17.274	6.623	9.354
sig.	.003**	.000***	.000***	.000***	.000***

Note. GRF = Ground Reaction Force; W/O BS = Without Backstep; PBS = Preferred Backstep; Δr = vertical displacement; $\Delta \alpha$ = angle change; ϵ = leg lengthening constant; k = leg stiffness. Superscript letters denote significant differences between the corresponding types at $p < .05$. ** $p < .01$. *** $p < .001$.

Table 4. Ground Reaction Force and Stiffness in Distance Variation Types

	Normalized peak vertical GRF (N)	Δr (m)	$\Delta \alpha$ (deg)	ϵ (mm/deg)	k (kN/m)
PB#a	126.9 $\pm$ 15.7	0.15 $\pm$ 0.02	10.8 $\pm$ 2.8	15.0 $\pm$ 3.7	4.9 $\pm$ 0.7
LB#b	133.8 $\pm$ 21.0	0.16 $\pm$ 0.02	11.4 $\pm$ 1.1	14.5 $\pm$ 3.1	4.9 $\pm$ 1.0
CBS#c	134.2 $\pm$ 13.5	0.15 $\pm$ 0.03	14.0#a $\pm$ 3.1	11.0 $\pm$ 3.6	5.8 $\pm$ 1.8
SB#d	132.6 $\pm$ 14.4	0.14 $\pm$ 0.02	8.2#b,c $\pm$ 2.3	17.7#c $\pm$ 4.7	5.9 $\pm$ 1.2
DSB#e	127.3 $\pm$ 15.4	0.16 $\pm$ 0.03	13.9#d $\pm$ 1.9	11.7#d $\pm$ 3.1	4.9 $\pm$ 1.3
f	.487	1.496	10.226	5.447	1.503
sig.	.745	.219	.000***	.001***	.217

Note. GRF = Ground Reaction Force; PB = Preferred Backstep; LB = Long Backstep; CBS = Cross Backstep; SB = Short Backstep; DSB = Double Short Backstep; Δr = vertical displacement; $\Delta \alpha$ = angle change; ϵ = leg lengthening constant; k = leg stiffness. Superscript letters denote significant differences between the corresponding types at $p < .05$. *** $p < .001$.

4. Discussion

Our investigation revealed distinct patterns in leg stiffness during Taekwondo roundhouse kicks that differ significantly from other athletic movements. The observed leg stiffness values (4.3-7.0 kN/m) were markedly lower than those reported across various locomotor activities. Farley and Gonzalez (1996) reported that during running at 2.5 m/s, leg stiffness varied from 7.03 kN/m at 30% stride frequency to 16.34 kN/m at 40% stride frequency. Even more striking differences emerge when comparing our results to maximal running conditions, where Michael and Blickhan (2002) documented leg stiffness values of 23 kN/m with peaks reaching 33 kN/m.

These differences become particularly noteworthy when considering other athletic activities. Jeon et al. (2002) reported leg stiffness values of 14.5 kN/m during dancers' jumps at normal height, increasing to 29.3 kN/m at maximum jump height. In long jumping, Seyfarth et al. (2002) documented simulation leg stiffness of 16.2 kN/m with a leg lengthening constant of 3.07 mm/deg. Further comparisons with hopping activities reveal additional insights - Granata et al. (2002) found that males demonstrate higher stiffness values than females during hopping, with stiffness increasing proportionally with hopping frequency. Ross

(2008) observed that athletes exhibited leg stiffness around 20 kN/m during single-leg hopping, compared to 14 kN/m in non-athletes.

Our findings show significantly higher leg lengthening constants (9.5-22.9 mm/deg) and lower leg stiffness values (4.3-7.0 kN/m) compared to these previous studies. This distinctive pattern can be attributed to the fundamental differences in force generation requirements between kicking and locomotor activities. While activities like long jumping, running, and jumping generate large ground reaction forces through approach runs or preparatory movements, Taekwondo kicks emphasize force generation in the kicking leg rather than the supporting leg.

The angular variation analysis revealed interesting patterns in both mechanical and performance aspects. In the 0°, 22°, and 45° conditions, while showing higher ground reaction forces, these positions demonstrated larger leg stiffness values due to reduced vertical displacement of the body's center of mass. This aligns with Falco et al.'s (2009) findings regarding the relationship between execution distance and mechanical parameters. The observed inverse relationship between backstep angle and leg stiffness suggests a biomechanical trade-off between stability and mobility requirements during defensive movements.

The biomechanical demands of the roundhouse kick proved particularly complex when examining the interaction between angular variations and distance parameters. As Kong et al. (2000) demonstrated, the movement requires precise coordination between the supporting leg's stabilizing function and the kicking leg's force generation. Our analysis revealed that the supporting leg demonstrated significant differences in normalized maximum vertical GRF across angles ($F = 4.088$, $p < .01$), supporting Estevan et al.'s (2011) findings about distance effects on mechanical parameters.

Distance variations showed distinct patterns from angular changes, particularly in terms of their effects on temporal and force characteristics. The preferred backstep distance exhibited optimal combinations of contact time and force generation capability, suggesting that experienced practitioners naturally select stepping distances that maximize both stability and power generation potential. This optimization appears to be based on individual anthropometric characteristics and training adaptations, as evidenced by the consistent patterns observed within skill levels despite variations in participant physical characteristics.

The temporal characteristics also showed distinctive patterns that varied systematically with both angle and distance parameters. Expert performers demonstrated significantly faster execution times ($M = 0.25$ s, $SD = 0.06$) compared to novices ($M = 0.32$ s, $SD = 0.10$), aligning with Menescardi et al.'s (2015) observations about the importance of execution speed in competition success. This temporal advantage appears to be achieved through superior neuromuscular control and movement efficiency, particularly in the transition between the defensive step and offensive kick initiation, which aligns with findings from Chang et al. (2021) regarding power and reaction time in martial arts techniques.

An important finding emerged regarding the relationship between leg stiffness modulation and performance effectiveness. The systematic decrease in leg stiffness with increasing backstep angle (from 7.0 kN/m at 0° to 4.3 kN/m at 90°) suggests that practitioners automatically adjust their lower limb mechanics to optimize the balance between stability and mobility. This adaptation appears to be more sophisticated than previously recognized, involving coordinated adjustments in multiple biomechanical parameters including contact time, force application, and center of mass control.

The implications of these findings extend beyond simple mechanical descriptions to practical applications in both training and competition. As Tang et al. (2007) observed, successful performance in modern Taekwondo requires precise control of leg stiffness across varying distances and angles. The significantly lower leg stiffness values we observed suggest that traditional training approaches based on locomotor patterns may need modification for optimal kick performance. Additionally, the distinct patterns of leg stiffness modulation across different defensive scenarios indicate that training programs should incorporate specific exercises targeting these unique biomechanical demands.

These mechanical characteristics provide new insights into the principles underlying effective defensive movement in Taekwondo. Understanding the relationship between footwork patterns and leg stiffness modulation can inform technique selection and training methodology, potentially leading to improved performance outcomes in competitive settings. The observed patterns of leg stiffness adaptation suggest that successful performers develop sophisticated control strategies that allow them to maintain both defensive effectiveness and counterattack capability across a range of movement conditions.

5. Practical Applications.

The findings from this biomechanical analysis of defensive footwork patterns provide valuable insights for Taekwondo coaches and practitioners. Traditional training approaches based on running or jumping mechanics may need modification, as the observed leg stiffness values (4.3-7.0 kN/m) were notably lower than those reported in other athletic activities. Coaches should develop specialized leg strength training programs that account for these unique biomechanical demands, particularly focusing on the coordination between supporting leg stability and kicking leg force generation.

When designing training programs, coaches should incorporate exercises at various backstep angles (0° to 90°) to help athletes develop adaptive leg stiffness control. The inverse relationship between backstep angle and leg stiffness suggests a progressive training approach, starting with smaller angles (0°-45°) where stability is higher before advancing to larger angles. This systematic progression can help practitioners develop the sophisticated control strategies needed for effective defensive movements.

Athletes can optimize their performance by focusing on their preferred backstep distance, which demonstrated optimal combinations of contact time and force generation capability. Practice sessions should emphasize transitions between defensive movements and counterattacks at varying angles, maintaining a forward-oriented upper body position for efficient attack initiation. The temporal characteristics observed in expert performers ($M = 0.25$ s, $SD = 0.06$) provide useful benchmarks for performance assessment and goal setting.

The findings of this study, however, should be considered within certain contextual limitations. The exclusive inclusion of male, right-leg dominant athletes in the study restricts the generalizability of

these findings across different populations. Additionally, the laboratory conditions, while precisely controlled, may not fully replicate the dynamic demands of competition environments. Future research should examine leg stiffness characteristics in female athletes, investigate the relationship between leg stiffness and injury prevention, and evaluate the impact of different training interventions on leg stiffness adaptation. Furthermore, studying these biomechanical parameters under competition conditions and fatigue states would provide valuable insights for practical application.

These biomechanical insights can significantly inform technique selection and training methodology, potentially leading to improved performance outcomes in competitive settings. Understanding the relationship between footwork patterns and leg stiffness modulation enables coaches and athletes to develop more effective training strategies that specifically target the unique demands of Taekwondo defensive movements and counterattacks. The findings of this study, while revealing important biomechanical characteristics of Taekwondo movements, should be interpreted cautiously given our relatively small sample size. While our participants were skilled collegiate Taekwondo athletes, further research with larger and more diverse samples would be necessary before broadly generalizing these results to all elite performers.

The study focused on highly skilled collegiate Taekwondo athletes with extensive competitive experience (8.9 ± 1.1 years of training), providing insights specifically relevant to advanced practitioners. The controlled laboratory environment, utilizing precise motion capture and force plate measurements, allowed for detailed biomechanical analysis but may present different conditions from dynamic competition scenarios. The sample consisted of specifically selected elite male athletes to ensure homogeneity in skill level and physical characteristics, which helped

establish clear biomechanical patterns for this specific population. Future research could build upon these findings by expanding to different skill levels, investigating adaptations across various training phases, and examining performance under competition-specific conditions. Additionally, exploring these parameters in relation to different training methodologies and their long-term effects on performance enhancement would provide valuable insights for comprehensive athlete development programs.

Funding: This research was funded by the Ministry of Education of the Republic of Korea and the National Research Foundation of Korea (NRF-2023S1A5B5A16080368)

Acknowledgments: In this section you can acknowledge any support given which is not covered by the author contribution or funding sections. This may include administrative and technical support, or donations in kind (e.g., materials used for experiments).

Conflicts of Interest: The authors declare no conflict of interest.

References

- Camomilla, V., Dumas, R., & Cappozzo, A. (2020). Human movement analysis: The soft tissue artefact issue. *Journal of Biomechanics*, 103, 109632.
- Chang, S. T., Evans, J., Crowe, S., Zhang, X., & Shan, G. (2021). An innovative approach for real-time determination of power and reaction time in a martial arts quasi-training environment using 3D motion capture and EMG measurements. *Archives of Budo*, 17, 275-290.
- Estevan, I., Falco, C., & Jandacka, D. (2011). Mechanical analysis of the roundhouse kick according to the stance position. *Portuguese Journal of Sport Sciences*, 11(2), 215-218.
- Falco, C., Alvarez, O., Castillo, I., Estevan, I., Martos, J., Mugarra, F., & 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.
- Farley, C. T., & Gonzalez, O. (1996). Leg stiffness and stride frequency in human running. *Journal of Biomechanics*, 29(2), 181-186.
- Farley, C. T., Houdijk, H. H. P., Van Strien, C., & Louie, M. (1998). Mechanism of leg stiffness adjustment for hopping on surfaces of different stiffnesses. *Journal of Applied Physiology*, 85, 1044-1055.
- Gavagan, C. J., & Sayers, M. G. (2017). A biomechanical analysis of the roundhouse kicking technique of expert practitioners: A comparison between the martial arts disciplines of Muay Thai, Karate, and Taekwondo. *PloS one*, 12(8), e0182645.
- Granata, K. P., Padua, D. A., & Wilson, S. E. (2002). Gender differences in active musculoskeletal stiffness. Part II. Quantification of leg stiffness during functional hopping tasks. *Journal of Electromyography and Kinesiology*, 12(2), 127-135.
- Huang, T. Y., Tang, W. T., Liu, T. T., Hamill, J., & Hu, C. (2022). Kinematic and kinetic demands on better roundhouse kick performances. *Sports Biomechanics*, 1-15.
- Jeon, H. S., Choi, J. D., & Hwang, B. Y. (2002). Leg stiffness control during drop landing movement in individuals with mechanical low back pain. *Sports Biomechanics*, 11(1), 57-71.
- Koh, J. O., & Watkinson, E. J. (2002). Possible concussions following head blows in the 2001 Canadian National Taekwondo Championships. *Cross Boundaries*, 1, 79-93.
- Kong, P. W., Luk, T. C., & Hong, Y. (2000). Difference between Taekwondo roundhouse kick executed by the front and back leg. In *Proceedings of XVIII International Symposium on Biomechanics in Sports* (pp. 272-275). Hong Kong.
- Kwok, H. H. M. (2022). Biomechanical characteristics of taekwondo axe kick and the effects of target distance. *Applied Sciences*, 12(3), 1139.
- McMahon, T. A., & Cheng, G. C. (1990). The mechanics of running: How does stiffness couple with speed? *Journal of Biomechanics*, 23(S1), 65-78.
- Menescardi, C., Lopez-Lopez, J. A., Falco, C., Hernandez-Mendo, A., & 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.
- Michael, G., & Blickhan, R. (2002). Joint stiffness of the ankle and the knee in running. *Journal of Biomechanics*, 35(11), 1459-1474.
- Moenig, U. (2017). Dominant features and negative trends in the current World Taekwondo Federation (WTF) competition system. *Ido Movement for Culture. Journal of Martial Arts Anthropology*, 17(3), 36-43.
- Park, S. H., Kim, J. S., & Kim, J. H. (2019). Effects of Taekwondo footwork training on dynamic balance and lower extremity strength in adult beginners. *International Journal of Environmental Research and Public Health*, 16(21), 4240.
- Preuschl, E., Hassmann, M., & Baca, A. (2016). A kinematic analysis of the jumping front-leg axe-kick in taekwondo. *Journal of Sports Sciences*, 34(12), 1124-1131.
- Ross, A. C. (2008). The effect of training status on inter-limb joint stiffness regulation during repeated maximal sprints. *Journal of Science and Medicine in Sport*, 11(1), 1-6.
- Seyfarth, A., Friedrichs, A., Wank, V., & Blickhan, R. (1999). Dynamics of the long jump. *Journal of Biomechanics*, 32(12), 1259-1267.
- Seyfarth, A., Geyer, H., Günther, M., & Blickhan, R. (2002). A movement criterion for running. *Journal of Biomechanics*, 35(5), 649-655.
- Tang, W. T., Chang, J. S., & Nien, Y. H. (2007). The kinematics characteristics of preferred and non-preferred roundhouse kick in elite Taekwondo athletes. *Journal of Biomechanics*, 40(S2), S780.