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ORIGINAL

Effects of Fatigue Induction on Ground Reaction Force Components, Postural Stability, and Vertical Jump Performance in Taekwondo Athletes

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Objective: The purpose of this study was to investigate the effect of fatigue induction on ground reaction force (GRF) components, postural stability, and vertical jump performance in Taekwondo athletes.

Method: Ten Taekwondo athletes (5 men, 5 women; mean age, 22.30 ± 2.62 years; mean height, 174.21 ± 9.20 cm; mean body weight, 67.28 ± 12.56 kg) participated in this study. Fatigue was induced by a short period of strenuous exercise performed on a motorized treadmill. The analyzed variables included vertical jump performance, static stability (mediolateral [ML], center of pressure [COP], anteroposterior [AP] COP, ΔCOPx, ΔCOPy, and COP area), postural stability index values (ML stability index [MLSI], AP stability index [APSI], vertical stability index [VSI], dynamic postural stability index [DPSI]), and GRF components (ML force, AP force, peak vertical force [PVF], and loading rate). To analyze the variables measured in this study, PASW version 22.0 was used to calculate the mean and standard deviation, while a paired *t*-test was used to evaluate the pre- versus post-fatigue results. Pearson's correlation coefficients among variables were also analyzed. The statistical significance level was set at $\alpha = .05$.

Results: Vertical jump performance decreased significantly after the induction of fatigue, while AP COP, ΔCOPx, COP area, APSI, VSI, and DPSI increased significantly. PVF and loading rate increased significantly after the induction of fatigue, while the postural stability variables (AP COP, ΔCOPy, COP area, APSI, VSI, DPSI) were similarly correlated with GRF components (PVF, loading rate) after fatigue was achieved ($r = .600$, $R^2 = 37\%$).

Conclusion: These results suggest that the induction of fatigue can decrease postural stability and exercise performance of Taekwondo athletes during training and competition sessions.

Keywords: Taekwondo, Fatigue, Postural stability, Vertical jump, Ground reaction force

INTRODUCTION

Taekwondo sparring requires a stable defense and quick attacks in a variety of conditions created by the opponent. Attack techniques involve great difficulty and continuous movements (Heller et al., 1998), and excellent lower-extremity strength and power are critical for roundhouse kicks, side kicks, front kicks, and repetitive jump kicks (Abidin & Adam, 2013; Roschel et al., 2009; Noorul, Pieter, & Erie, 2008; Dizon & Grimmer-Somers, 2012; Elsawy, 2010). Power is an outcome of the athlete's force applied and speed (Reiser, Rocheford, & Armstrong, 2006; Rochel et al., 2009). Vertical jump performance can indirectly predict the explosive power of the lower extremities and is intimately related to kinematic function (Roschel et al., 2009; Noorul et al., 2008; Dizon & Grimmer-Somers, 2012; Markovic & Jaric, 2007).

On the other hand, defense techniques are dependent upon an athlete's left and right leg performance as well as postural stability (Kim, Kim, & Shin, 2011). However, it is difficult to maintain balance during kicks, and more strength and energy are needed for the lower extremities (Serina & Kieu, 1991) since kicks account for about 80% of all offensive techniques (Falcó & Estevan, 2015). This may induce fatigue in Taekwondo athletes during training and competition, which may expose them to injury (Hssin et al., 2015) or hinder them from accomplishing their individual goals (Wojciechowska-Maszkowska, Borysiuk, Wasik, Janisiów, & Nawarecki, 2012).

Injury is a physical maladaptation caused by the delivery of energy that surpasses one's physical capabilities to maintain structural and functional completeness (Lystad, Pollard, & Graham, 2009; Ziaee, Rahmani, & Rostami, 2010). Approximately 36% of injuries in Taekwondo athletes occur during training, while 54% occur during competition (Kazemi, Shearer, & Choung, 2005). The most frequently injured site is the lower extremities (46.5%), followed by the upper extremities (18%), back (10%), and head (3.6%) (Kazemi et al., 2005), and the prevalence of injury is higher in Taekwondo than in karate, hapkido, kungfu, tai chi chuan, ice hockey, and basketball (Lystad et al., 2009; Zetaruk, Violan, Zurakowski, &

Micheli, 2005; Pieter, 2005). More importantly, injury during Taekwondo is closely related to fatigue, as 7.5% of injuries occur during round 1 and 43.1% occur during round 2, while 43.1% occur during round 3, the final round (Hssin et al., 2015).

Fatigue refers to a phenomenon in which muscles fail to produce strength during contraction or respond to contraction signals (Asmussen, 1979; Gibson & Edwards, 1985), and it is a complex phenomenon that encompasses a variety of areas in the nervous system (Boyas et al., 2011; Boyas & Guével, 2011). Fatigue is a critical factor for athletes since it induces lateral ankle sprain (Gutierrez, Jackson, Dorr, Margiotta, & Kaminski, 2007) and reduces muscle strength, the dynamic properties of proprioception, and other capabilities required for improving balance (Chabran, Maton, & Foument, 2002; Forestier, Teasdale, & Nougier, 2002; Harkins, Mattacola, Uhl, & Malone, 2005; Hiemstra, Lo, & Fowler, 2001). These results reportedly influence coordination as well as posture control, further increasing the incidence of injury (Chabran et al., 2002; Price, Hawkins, Hulse, & Hodson, 2004).

As shown here, fatigue in Taekwondo athletes may affect agility, posture control, and dynamic variables. However, most studies to date have only surveyed the ground reaction force associated with a specific technique, such as that between two legs during a 360° roundhouse kick during warm-up and the optimal condition preferred by individuals (Lee & Huang, 2013), kick performance according to stance (0°, 45°, 90°) (Estevan et al., 2013), kinematical analysis of a 540° backspin kick (Kang, Kang, & Yu, 2013), and differences in Taekwondo kicks by dominant and non-dominant legs (Kim & Kim, 2010).

In particular, Park, Jun, Park, Ryoo, & Choi (2002) reported that male and female Taekwondo athletes have significantly increased heart rate, blood lactate levels, blood pressure, and myocardial oxygen consumption after three competition rounds. Another study reported that prolonged Taekwondo training affects the maximal oxygen uptake and anaerobic threshold (Kang, Shin, & Chung, 2009) since Taekwondo matches comprise three 2-minute rounds with 1-minute breaks but are extended to a fourth round when a tied score occurs. Furthermore, although Taekwondo matches require accurate and quick kicks to the target, fatigue caused by muscular exertion hinders afferent feedback and damages joint proprioception and kinesthetic properties (Bizid et al., 2009; Harkins et al., 2005), resulting in agonistic kicks and landings. Since the incremental maximal exercise performed in Taekwondo matches may induce systemic fatigue in athletes, it is necessary to closely examine the effects of fatigue on vertical jump performance, postural stability upon landing, and other kinematical variables.

In this context, the objective of the present study is to examine the effects of fatigue on vertical jump performance, postural stability, and ground reaction forces by inducing exhaustion using an incremental maximal exercise test in Taekwondo athletes. This study also compares the correlations among variables to identify their similarities and contrasting features to aid Taekwondo athletes and their coaches.

METHODS

1. Subject

The subjects of this study were college and professional athletes (5 men, 5 women) with >10 years of experience (Table 1). Each athlete was fully capable of performing vertical jump, landing, and treadmill running motions. The investigator provided an adequate explanation of the study purpose and contents, and only those who understood and voluntarily consented to the terms were included in the study. In addition, the investigator asked the subjects about the leg that they most frequently use during their daily routines and competitions and determined that the right leg was dominant for all.

Table 1. Subjects' characteristics (mean ± SD)

Sex	Age (years)	Height (cm)	Body weight (kg)
Female (n = 5)	21.80 ± 1.92	169.90 ± 4.92	58.38 ± 3.68
Male (n = 5)	22.80 ± 3.34	180.52 ± 3.34	76.18 ± 11.98
	22.30 ± 2.62	174.21 ± 9.20	67.28 ± 12.56

2. Experimental procedure

All subjects wore lightweight T-shirts and shorts and independently performed warm-ups. In a pre-test, each subject performed a vertical jump, single-leg balance, and drop landing. After fatigue was induced on a treadmill, the same procedures were performed again in the post-test. To maintain fatigue, the drop landing was performed within 3 m of the treadmill and the bilateral vertical jump and single-leg balance were assessed on a force plate.

First, the subjects performed the single-leg balance for about 20 seconds on the force plate (AMTI-OR-7, USA) with visual information, from which 10 seconds of data were randomly sampled at a rate of 1,000 Hz. To assess the drop landing under identical conditions, the subjects were positioned at a consistent height (40 cm) and instructed to place both hands on the anterior superior iliac spine before landing.

Fatigue was induced via the Bruce protocol (Bruce, Kusumi, & Hosmer, 1973) on a treadmill, and a physiologist conducted an incremental maximal exercise test until the subjects reached an all-out state. The post-test was performed within 1 minute immediately following the induction of fatigue in the same order performed in the pre-test (Fagenbaum & Darling, 2003; Harkins et al., 2005; Kim & Youm, 2015). The single-leg balance test was performed with the dominant (right) leg only.

3. Data collection and analysis

The vertical jump was performed on a force plate. The height (h) of the center of mass was calculated by the application of flight time

(t_{flight}) to the equation of motion (Bosco et al., 1983) as follows:

$$h = \frac{1}{8} g (t_{flight})^2$$

For postural stability, static and dynamic stabilities were assessed. Static postural stability was measured by taking the integral of the anteroposterior (AP) center of pressure (COP), mediolateral (ML) COP (Michell, Ross, Blackburn, Hirth, & Guskiewicz, 2006) and the maximal and minimal changes created by the path of the COP (Hyun & Ryew, 2014).

$$M-LCOP = \frac{\sum_{t=0}^{T} \left| COP_{x,t} - COP_{x,mean} \right|}{T}$$

$$A-PCOP = \frac{\sum_{t=0}^{T} \left| COP_{y,t} - COP_{y,mean} \right|}{T}$$

$$COP_{area} = \int_{t1}^{t2} \Delta COPx \cdot \Delta COPy$$

Higher COP values signify lower stability of the ML COP (COPx) and AP COP (COPy).

Wikstrom, Tillman, Smith, & Borsa (2005) suggested a new method of assessing dynamic postural stability using force plates. However, since it is difficult to clearly pinpoint the termination time after landing, the time function increases, which may induce stability coefficient errors. Therefore, we assessed precision based on the period from the moment the right foot contacts the ground until the point at which the first peak vertical force (PVF) is created (Hyun & Ryew, 2014). Higher values for each direction indicate lower stability, while lower values indicate higher stability.

$$MLSI = \sqrt{\sum (0 - Fx_{max})^2 / samples}$$

$$APSI = \sqrt{\sum (0 - Fy_{max})^2 / samples}$$

$$VSI = \sqrt{\sum (0 - Fz_{max})^2 / samples}$$

$$DPSI = MLSI + APSI + VSI$$

Kwon GRF 2.0 (Visol, Korea) and Excel 2007 (Microsoft, USA) were used to analyze the mediators of ground reaction force, while the computed data were processed with PASW 22.0 (IBM, USA) to compute the means (M) and standard deviation (SD). Paired *t*-tests were performed according to the athletes' pre- or post-fatigue states, while Pearson's correlation coefficients were used to analyze the correlations among the variables. Statistical significance was set at α = .05.

RESULTS

The fatigue intensity induced by the treadmill during the incremental exercise test can be expressed as a maximal oxygen uptake per kilogram (VO_2max/kg) of 54.50 ± 10.94 $mL \cdot min^{-1} \cdot kg^{-1}$ and a minute ventilation (VE) of 92.72 ± 29.66 $L \cdot min^{-1}$ (Heller et al., 1998; Toskovic, Blessing, & Williford, 2002, 2004; Jo & Kim, 2001; Kim, 1998).

1. Changes in vertical jump performance and static stability

Figure 1 and Table 2 shows the results of the vertical jump performance and static stability under an induced fatigue condition in the male and female Taekwondo athletes.

Vertical jump performance was significantly reduced after fatigue was induced ($p < .001$). During single-leg balance on the right (dominant) leg, AP COP, ΔCOPy, and COP area increased significantly after fatigue was induced ($p < .05$), while there were no significant changes in ML COP or ΔCOPx ($p > .05$).

Table 2. Vertical jump performance and static stability index

Factor	Pre-test (M ± SD)	Post-test (M ± SD)	Δ%	*t*	*P*
Vertical jump (m)	0.54 ± 0.06	0.50 ± 0.07	-7.40	4.511	.001***
Mediolateral COP	0.29 ± 0.09	0.22 ± 0.07	-24.13	.715	.492
Anteroposterior COP	0.21 ± 0.11	0.40 ± 0.20	90.47	2.490	.034*
ΔCOPx (cm)	2.39 ± 1.75	2.97 ± 0.83	24.26	.867	.408
ΔCOPy (cm)	2.37 ± 0.85	4.84 ± 1.91	104.21	3.607	.006**
COP area (cm^2)	5.81 ± 4.72	14.09 ± 6.45	142.51	3.558	.006**

***$p < .001$, **$p < .01$, *$p < .05$

2. Changes in ground reaction force components and dynamic stability index

As shown in Table 3, we compared the changes in ground reaction force components and dynamic postural stability index during drop landing before versus after fatigue and found that ML force, AP force, and MLSI were not significantly changed ($p > .05$), whereas PVF, loading rate, APSI, VSI, and DPSI increased significantly ($p < .01$).

3. Correlations among variables

The results of the correlation analysis for vertical jump performance, static and dynamic postural stability index, and ground reaction force components are shown in Table 4. To identify the similarities in percen-

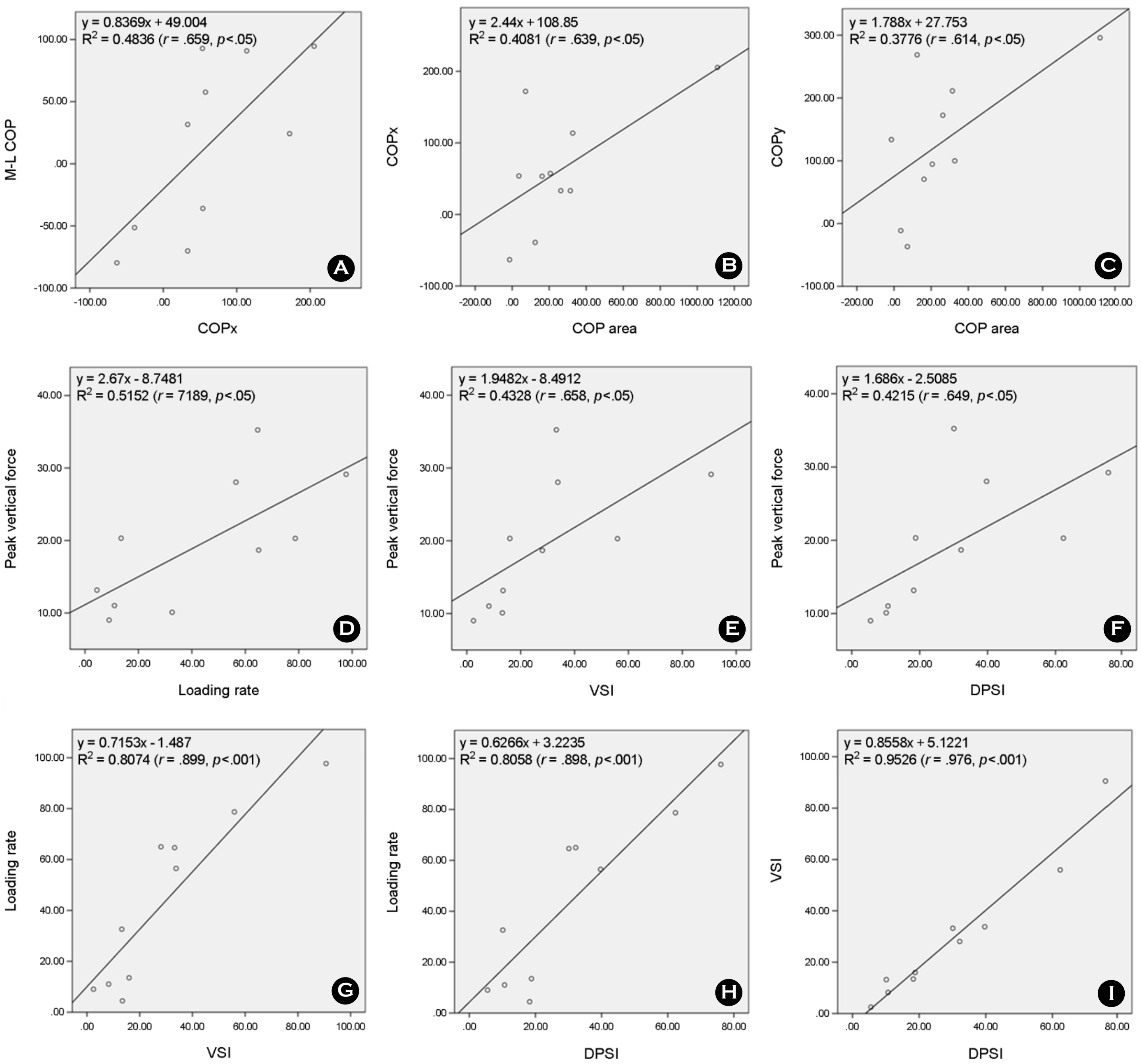

Figure 1. Scatter plot and coefficient of determination

tage reduction and percentage increase, high coefficients of $r > .600$ were stated.

The following strong correlations were noted: $r = .695$ ($R^2 = 0.483$, $p < .05$) between ML COP and COPx; $r = .639$ ($R^2 = 0.408$, $p < .05$) between COP area and COPx; and $r = .614$ ($R^2 = 0.377$, $p < .05$) between COP area and COPy. There were the following high explanatory power and statistically significant correlations: $r = .718$ ($R^2 = 0.515$, $p < .05$) between PVF and loading rate; $r = .658$ ($R^2 = 0.432$, $p < .05$) between VSI and PVF; and $r = .649$ ($R^2 = 0.421$, $p < .05$) between DPSI and PVF.

The following strong statistically significant correlations were also seen: $r = .899$ ($R^2 = 0.807$, $p < .001$) between loading rate and VSI; $r = .898$ ($R^2 = 0.805$, $p < .001$) between DPSI and loading rate; and $r = .976$ ($R^2 = 0.952$, $p < .001$) between VSI and DPSI.

DISCUSSION

Taekwondo athletes' blood lactate concentrations and heart rates reportedly increased rapidly during competitions (Herror et al., 1998), first starting to increase in rounds 1 and 2 and peaking in round 3 (Butios & Tasika, 2007). Hence, the present study involved incremental

Table 3. Ground reaction force parameter and dynamic postural stability index

Factor	Pre-test (M ± SD)	Post-test (M ± SD)	Δ%	*t*	*p*
Mediolateral force (N/BW)	0.36 ± 0.36	0.50 ± 0.25	36.93	1.163	.275
Anteroposterior force (N/BW)	0.06 ± 0.27	0.09 ± 0.32	50.18	.223	.828
Peak vertical force (N/BW)	4.43 ± 1.27	5.25 ± 1.31	18.14	7.611	.000***
Loading rate (N/BW · sec^{-1})	89.86 ± 32.11	122.93 ± 33.72	36.80	4.434	.002**
MLSI	1.36 ± 0.52	1.60 ± 0.47	16.95	1.526	.161
APSI	3.39 ± 0.70	4.79 ± 1.31	41.61	3.678	.005**
VSI	24.37 ± 5.63	30.67 ± 4.96	25.85	4.411	.002**
DPSI	29.12 ± 6.54	37.06 ± 5.82	27.27	4.877	.001***

****p* < .001, ***p* < .01

Table 4. Correlationship relative to vertical jump performance and GRF components (unit: *r*)

Factor	ML COP	AP COP	ΔCOPx	ΔCOPy	COParea	ML force	AP force	PVF	Loading rate	MLSI	APSI	VSI	DPSI
Vertical jump	.034	-.238	.191	.015	.207	.502	.459	-.020	-.266	.001	-.096	-.197	-.198
ML COP		.240	.695* (A)	-.020	.539	.352	.443	-.539	-.226	.165	.099	-.455	-.386
AP COP			-.142	.589	.362	-.163	-.102	-.239	-.090	-.239	-.419	-.242	-.326
ΔCOPx				-.149	.639* (B)	.415	.056	-.491	-.111	-.276	.224	-.325	-.264
ΔCOPy					.614* (C)	-.596	.041	-.093	-.253	-.030	-.592	-.284	-.429
COP area						.029	.165	-.440	-.254	-.356	-.484	-.437	-.524
ML force							.308	-.103	.056	-.332	.389	-.036	.017
AP force								.255	.043	.494	.026	-.057	-.022
PVF									.718* (D)	.125	.189	.658* (E)	.649* (F)
Loading rate										-.190	.435	.899*** (G)	.898*** (H)
MLSI											.063	-.112	-.017
APSI												.349	.532
VSI													.976*** (I)

****p* < .001, **p* < .05

exercise on a treadmill to mimic the typical systemic fatigue induced by a Taekwondo match (three 2-minute rounds with 1-minute breaks between) and examined the changes in the athletes' vertical jump performance, postural stability, and ground reaction components.

First, vertical jump performance was statistically significantly reduced in the post-test (0.50 ± 0.07 m) compared to the pre-test (0.54 ± 0.06 m). Park, Youm, & Kim (2015) analyzed vertical jump performance according to fatigue degree in healthy male (n = 21) and female (n = 21) adults in their twenties and found that pre-fatigue jump performance was 44.8 cm, post-50% fatigue was 40.8 cm, and post-30% fatigue was 38 cm for men and 32.9 cm, 31.6 cm, and 31.4 cm for women, respectively. Since the subjects of the present study were professional male and female Taekwondo athletes, the mean baseline jump performance was relatively higher than that of non-athletes, but the athletes showed greater performance reductions according to fatigue degree to levels to those of the prior study. Gastin (2001) reported that changes in Taekwondo athletes' aerobic energy systems are associated with changes in their physical energy systems and that they influence their vertical jump performance. Furthermore, lower extremity strength is crucial for jump kicks and maintaining posture while performing offensive techniques in Taekwondo (Fong & Ng, 2011). Hence, fatigue is thought to further reduce the performance capabilities required for offensive and defensive techniques during training or sparring, such as explosive muscle strength, jump performance, and jump kicks (Chiodo et al., 2011).

The analysis of static stability showed no significant differences in ML COP, ∆COPx, or MLSI of dynamic postural stability after fatigue was induced, whereas AP COP, ∆COPy, COP area, APSI, VSI, and DPSI decreased considerably. For Taekwondo, flexion-extension motions of the hip, knee, and ankle joints are critical to achieving instantaneous AP movements of the body's center of mass, trunk slope, and kick motions for offensive and defensive techniques (Chiodo et al., 2011; Ha, Yoon, & Kim, 2011; Ha & Kim, 2012). Furthermore, controlling movement in the AP rather than ML direction of the COP plays a key role in exercise that involves frequent flexion-extension motions (Winter, Prince, Frank, Power, & Zabjda, 1996), while the accumulation of fatigue reduces dynamic stability, balance control, and motion control (Johnston, Howard, Cawley, & Loss, 1998). In particular, Gribble & Hertel (2004) induced fatigue in nine women and four men and found a significant difference in AP COP but not ML COP. Similarly, the AP performance of the male and female Taekwondo athletes in the present study is presumed to have been more greatly affected than the ML performance after fatigue was induced, which might have influenced their static stability.

Despite the correlation between (r = .659) and the explanatory power (48%) of ML COPy and MLSI (Figure 1A), fatigue had no significant effect on postural stability. Lee, Song, Young (2000) defined the early stage of lateral ligament damage due to ankle sprain as the acute phase and the chronic stage as over-training, over-use, and failure of recovery of past injury, reporting that up to approximately 74% of cases could progress to chronic ankle instability (Anandacoomarasamy & Barnsley, 2005; Beynnon, Renström, Alosa, Baumhauer, & Vacda, 2001). Considering these reports, future studies should perform a more in-depth survey of variables including fatigue, lateral ligament damage due to past sprains, and training type to identify the associations among them.

COP area is the integral of ∆COPx and ∆COPy, and there was a statistically significant correlation between them in that increased COP movement in the AP direction was correlated with increased area (Figure 1C, r = .614, R^2 = 37%). This finding indicates that fatigue increases COP vibrations to maintain postural stability, which is in line with the results reported by Kim, Shin, Jung, & Lee (2012), who suggested a strong correlation between the AP direction and areas of static stability variables of Taekwondo athletes. In addition, similar to the strong correlation between the ML direction and area according to fatigue reported by Kim et al. (2012), there was a high correlation (r = .639) and explanatory power (40%) between COP area and COPx (Figure 1B), although changes in COPx were statistically insignificant. As shown here, although postural maintenance of the dominant leg during exercise varies among athletes (Kim et al., 2012), COP movement in the AP direction considerably affects securing area, while COP movement in the ML direction is also presumed to be intimately related to maintaining postural stability.

We assessed the changes in ground reaction force components via a drop landing from a consistent height because Taekwondo athletes have different jumping heights and use different kick techniques during sparring. We found no significant changes in ML GRF and AP GRF after the induction of fatigue, but PVF significantly increased from 4.43 N/BW to 5.25 N/BW and loading rate increased from 88.86 N/BW · sec^{-1} to 122.93 N/BW · sec^{-1} after fatigue. There was a statistically significant correlation between PVF and loading rate (r = .719) and explanatory power of 51% (Figure 1D). The PVF results of frequently used techniques with high risk of injury during Taekwondo sparring were as follows: 1.62~2.44 N/BW for tornado kick (dolgae kick) (Yang, 2001), 1.09 N/BW for counter roundhouse kick in the proficient group and 1.29 N/BW for counter roundhouse kick in the non-proficient group (Ha et al., 2011), 3.14 N/BW for 540˚ turning hook kick (Lee, Kim, & Lee, 2014), and 5.63 N/BW for tornado kick (dolgae kick) by female Taekwondo athletes in the left foot and 1.78 N/BW in the right foot (Park, 2012).

The greatest external force is wielded on the body at the point at which the maximal vertical ground reaction force is created, so excessive ground reaction force on joints and muscles during landing may induce injury (Cerulli, Benoit, Lamontagne, Caraffa, & Liti, 2003; Hootman, Dick, & Agel, 2007; Miyama & Nosaka, 2004). Considering the findings of this study, strained landing motion in fatigued male and female Taekwondo athletes increases the shock per unit time on their bodies and prevents them from effectively controlling the ground reaction force, increasing the risk of injury.

Since the calculation of DPSI encompasses GRF in each direction based on an equal number of samples, there is a strong statistically significant correlation (correlation r > .600 with an explanatory power of 43%) between VSI and the increase of PVF and loading rate induced by fatigue as well as between DPSI (Figures 1E-1I). In particular, VSI—the stability index incorporating the vertical power component—was closely associated with PVF and loading rate. According to Wikstrom et al. (2005), balance maintenance during landing reflects shock absorption, and considering that DPSI is the sum of MLSI, APSI, and VSI, VSI is determined to have the greatest ability to decrease postural stability.

As such, fatigue induced in Taekwondo athletes via incremental exercise reduced vertical jump performance and static and dynamic stability in the AP direction and increased shock on the body, implying that these findings would be useful quantitative data for preventing injuries and boosting athletic performance during prolonged technical training of athletes.

CONCLUSION

The objective of this study was to identify the effects of fatigue on the vertical jump performance, postural stability, and ground reaction force components of Taekwondo athletes. Static stability was measured by analyzing the values and areas of AP COP and ML COP during right leg balance as well as three directional force components (ML force, AP force, and PVF), loading rate, and dynamic postural stability index (MLSI, APSI, VSI, DPSI) during a drop landing. The results indicated that vertical jump performance was significantly reduced in the post-test. In terms of postural stability, AP COP, ∆COPy, COP area, APSI, VSI, and DPSI were significantly increased in the post-test. Furthermore, PVF and loading rate were also significantly increased in the post-test. Finally, there was a strong correlation between reduced postural stability and increased ground reaction components (r > .600).

Data related to exercise performance according to fatigue level are useful for athletes who desire to increase their athletic performance. Hence, the correlations among various fatigue-related variables should be examined, while more male and female subjects should be recruited to more in-depth examinations of sex-specific changes in kinematic variables. Furthermore, future studies should examine the correlation between fatigue and body weight reductions since many Taekwondo athletes attempt to reduce their body weights to qualify for specific Taekwondo weight classes.

Conflict of Interest

The authors report no potential conflicts of interest relevant to this article.

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