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ORIGINAL

Effect of Functional Ankle Instability and Surgical Treatment on Dynamic Postural Stability and Leg Stiffness Variables during Vertical-Drop Landing

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Objective: The purpose of this study was to investigate the effect of functional ankle instability (FAI) and surgical treatment (ST) on postural stability and leg stiffness during vertical-drop landing.

Method: A total of 21 men participated in this study (normal [NOR]: 7, FAI: 7, ST: 7). We estimated dimensionless leg stiffness as the ratio of the peak vertical ground reaction force and the change in stance-phase leg length. Leg length was calculated as the distance from the center of the pelvis to the center of pressure under the foot. Furthermore, the analyzed variables included the loading rate and the dynamic postural stability index (DPSI; medial-lateral [ML], anterior-posterior [AP], and vertical [V]) in the initial contact phase.

Results: The dimensionless leg stiffness in the FAI group was higher than that of the NOR group and the ST group ($p = .018$). This result may be due to a smaller change in stance-phase leg length ($p = .001$). DPSI (ML, AP, and V) and loading rate did not show differences according to the types of ankle instability during drop landing ($p > .05$).

Conclusion: This study suggested that the dimensionless leg stiffness was within the normal range in the ST group, whereas it was increased by the stiffness of the legs rather than the peak vertical force during vertical-drop landing in the FAI group. Identifying these potential differences may enable clinicians to assess ankle instability and design rehabilitation protocols specific for the impairment.

Keywords: Vertical-drop landing, Leg stiffness, Loading rate, Postural stability

INTRODUCTION

Lateral ligament sprain of the ankle commonly occurs during powerful jumping and cutting movements (Delahunt, Monaghan, & Caulfield, 2006; Hubbard-Turner & Truner, 2015), and is estimated to account for 15% of all sports-related injuries (Hotman, Dick, & Agel, 2007).

Among 447 patients diagnosed as having ankle sprain, 55~72.6% were reported to show residual symptoms, such as lateral ankle weakness or restricted jumping ability, at 6 weeks to 18 months post-injury (Braun, 1999; Gerber, Williams, Scovile, Arciero, & Taylor, 1998). However, approximately 55% of patients with ankle sprain avoid treatment by a health-care specialist (McKay, Goldie, Payne, & Oakes, 2001; Smith & Reischi, 1986), and the extent of ankle sprain has also been underestimated in athletes (Hertel, 2002).

Ankle sprain can cause more serious problems than is typically expected, making it difficult to maintain the previous level of physical activity (Hubbard-Turner & Turner, 2015). Therefore, when an ankle sprain occurs, the decline in athletic performance may not be properly resolved with general treatment methods (Braun, 1999; Smith & Reischl, 1986), and if the patient is not given appropriate treatment and rehabilitation time, chronic ankle instability (CAI) may develop. CAI can be caused by mechanical ankle instability, functional ankle instability (FAI), or a combination of the two factors (Tropp, Odenrick, & Gillquist, 1985; Wilkerson & Nitz, 1994).

FAI is caused by impaired neuromotor control, which includes elements of proprioception, muscle strength, muscle response time, and postural control (Richie, 2001). In particular, weaker proprioception in FAI not only delays the fibular response time but also negatively affects the balance of the limbs (Cornwall & Murrell, 1991; Löfvengerg, Kärrholm, Sudelin, & Ahigren, 1995). For this reason, patients with FAI show abnormal landing in contrast to healthy individuals, and slower time to stabilization in the anterior-posterior and medial-lateral axes (Brown, Ross, Mynark, & Guskiewicz, 2004; Caulfield & Garrett, 2002, 2004; Ross & Guskiewicz, 2004).

Table 1. Characteristics of subjects

Section	Age (years)	Height (cm)	Weight (kg)
Normal (NOR)	23.8 ± 0.6	177.2 ± 2.9	73.7 ± 4.7
Functional ankle instability (FAI)	21.8 ± 1.6	177.4 ± 6.9	82.7 ± 10.8
Surgical treatment (ST)	21.2 ± 1.8	175.2 ± 3.6	79.5 ± 21.0
Mean ± standard deviation	22.3 ± 1.8	176.6 ± 4.6	78.6 ± 13.7

In addition to these distinctive problems in postural control, when patients with FAI are exposed to impact force, they minimize joint movement to reduce the load on the joints (Thonnard, Bragard, Willems, & Plaghki, 1996). Moreover, positional sense deficits have been shown to increase the likelihood that patients will not find the ideal foot position to minimize the ground reaction force (GRF) before landing (Konradsen, Voigt, & Hojsgaard, 1997). These characteristics in patients with FAI are caused by altered patterns of motor control learning due to injury, and increase the stress on the joint cartilage by making the ankle less able to support a given loading rate (Caulfield & Garrett, 2004).

Thus, although athletes with FAI can achieve functional motor improvement with non-surgical treatment methods, problems recur in 20% of athletes, ultimately leading to motor impairment (Krips, van Dijk, Lehtonen, Halasi, & Moyen, 2002). When rehabilitation interventions are insufficient to maintain normal functional stability, surgical treatment (ST) is required (Krips et al., 2002). To date, various surgical methods have been used to treat CAI; however, typically, patients are treated with distraction and anatomical reconstruction using the modified Brostrom procedure (Brostrom, 1966; Karlsson, Bergsten, Lansinger, & Peterson, 1988, 1989). Coetzee, Ellington, Ronan, and Stone (2018) reported excellent outcomes after the Brostrom procedure, with the ligament in a stretched, normalized, and relaxed state over time; however, they also reported incomplete recovery of lower-limb mechanics (Fujimaki, Miyawaki, Thorhauer, Prisk, & Tashman, 2013).

Despite the extensive clinical and basic scientific research on ankle sprain to date, the recurrence rate remains high. In other words, the initial lower-limb mechanics during functional movements after FAI have been well investigated, and patients are provided with appropriate feedback. However, there are very few instruments with proven reliability, validity, and reactivity to assess the state of patients with various ankle injuries before and after treatment (Button & Pinney, 2004).

Individuals participating in sporting activity frequently perform jumping and landing movements in dynamic situations, which place excessive demands on ankle joint function. To restore the motor function of the lower limb in patients undergoing surgery and patients with FAI, it is very important to analyze and evaluate the functional differences in lower-limb mechanics during functional movements and landing. In particular, leg stiffness is closely related to the impact (N) and change in leg length (%) during landing from a jump (Farley, Glasheen, & McMahon, 1993), and a certain level of stiffness must be maintained for optimal athletic performance (Arampatzis, Brüggemann, & Metzler, 1999; Donelan & Kram, 2000; Farley & Gonzalez, 1996; McMahon & Cheng, 1990). However, while movements are performed by complex musculoskeletal systems of muscles, tendons, and ligaments (Farley & Gonzalez, 1996), the complex mechanisms involved in lower-limb function can be explained by leg stiffness (Arampatzis et al., 1999; Dutto & Smith, 2002; McMahon & Cheng, 1990). Our study can provide very useful information for patients who require ST for an ankle injury.

This study aimed to quantitatively analyze changes in postural stability, leg stiffness, and related variables, in order to evaluate the functional characteristics of the lower limb during vertical-drop landing in patients undergoing surgery and patients with FAI.

METHODS

1. Subjects

A total of 21 adult male subjects participated in the present study, consisting of 7 individuals with no musculoskeletal abnormalities of the lower limb (NOR group), 7 individuals diagnosed as having FAI (FAI group), and 7 individuals who had undergone surgery on the right ankle 1 year ago (ST group) (Table 1). The subjects had no difficulties in performing a vertical-drop task. The study was conducted according to the experimental procedure after receiving approval from the Incheon National University Institutional Review Board.

2. Experimental procedure

All subjects were first informed of their individual test time, and performed at least 30 min of warm-up exercises before the test to prevent injury. During the vertical-drop test, a motion analysis system consisting of eight video cameras (six Eagle and two Raptor Camera System; Motion Analysis Corp., USA) was used alongside two GRF sensors (OR6-5-2000; AMTI Inc., USA) to measure the kinetics and kinematics of the major joints of the lower limb. The eight cameras were installed anteriorly and to the left and right of the subject at a distance of <7 m. After setting up the environment to completely capture the range of motion, calibration was performed in order to set the spatial coordinates. The sampling rate of the video cameras was set to 120 frames/sec, and the accuracy was 0.3 mm. Finally, 15-mm reflective markers (a total of 19 markers) were placed on the subjects' lower limbs based on the Helen Hayes markers set before performing the vertical-drop test.

The vertical-drop test was designed with reference to a study on shock absorption strategies of body segments (Seegmiller & McCaw, 2003), using a height of 30 cm and a stable base. After taking three measurements for each subject, success or failure was evaluated based on assessments by the researcher and the subject.

Data on the GRF generated upon landing was collected at a sampling rate of 1,200 Hz, and were synchronized with the motion analysis data using an A/D converter (NI USB-6218; National Instruments, Hungary). All the kinetic and kinematic data were processed using Cortex 4 (Motion Analysis Corp., USA). The body was treated as a linked rigid body system. The center of the hip joint was found using joint center localization, and the center of weight of each segment was calculated using parametric estimate data for each segment (Plagenhoef, Evans, & Abdelnour, 1983). All video data were subjected to Butterworth low-pass digital filtering, with a cutoff frequency of 10 Hz.

3. Analysis and processing of data

In this study, to evaluate lower-limb function during vertical-drop landing, we focused on the dynamic postural stability index (DPSI) and leg stiffness. The detailed calculation methods are given below.

Leg stiffness (K_{leg}) was calculated using the method proposed by Silder, Besier, and Delp (2015). Leg length was calculated as the three-dimensional distance from the pelvis center to the center of pressure at the moment of initial contact, and at the moment of peak vertical force (PVF) (Hyun & Ryew, 2016, 2017) (Figure 1).

$$K_{\text{leg}} = \frac{\text{PVF}}{(l_{\text{o}} - l_{\min})/l_{\text{o}}}{}'.$$

Here, the normalized leg length (100%) was given by

$$l_{\text{o}}, l_{\min} = \sqrt{(X_{\text{pelvis}} - X_{\text{COP}})^2 + (Y_{\text{pelvis}} - Y_{\text{COP}})^2 + (Z_{\text{pelvis}} - Z_{\text{COP}})^2},$$

$Z_{\text{COP}} = 0$.

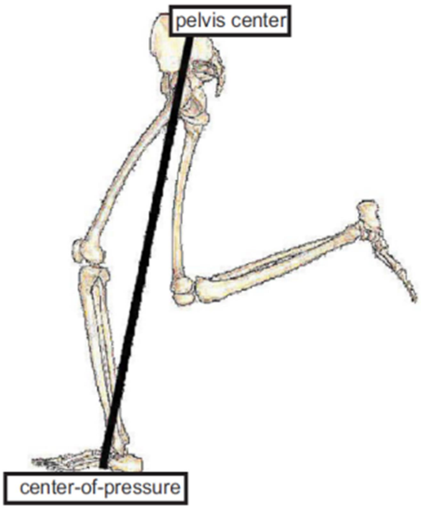

Figure 1. Leg length was estimated by calculating the distance from the center of pressure to the center of the pelvis (Delp et al., 1990; Silder et al., 2015).

PVF is the peak vertical force generated during the support phase, and the normalized value (N/BW) was calculated by dividing by each subject's body weight. l_{o} is the normalized leg length at the initial contact of the foot with the ground, and $l_{\min}$ is the leg length at PVF after landing. Here, as shown in Figure 1, the leg length was calculated as the three-dimensional distance from the center of pressure (Bullimore & Burn, 2006) to the center of the pelvis (Plagenhoef et al., 1983).

For the DPSI, we referred to Wikstrom, Tillman, Smith, and Borsa (2005); however, to set a clear endpoint after landing, we modified the time for evaluating the number of data points and the equation for the vertical direction. Although the zero point for GRF is the same, the endpoint was set as the moment of PVF (Hyun & Ryew, 2014).

Medial-lateral stability index (MLSI) = $\sqrt{[\Sigma(0 - x_{\text{PVF}})^2}$ / number of data points].

Anterior-posterior stability index (APSI) = $\sqrt{[\Sigma(0 - y_{\text{PVF}})^2}$ / number of data points].

Vertical stability index (VSI) = $\sqrt{[\Sigma(0 - z_{\text{PVF}})^2}$ / number of data points].

DPSI = $\sqrt{[\Sigma(0 - x_{\text{PVF}})^2 + \Sigma(0 - y_{\text{PVF}})^2 >+ \Sigma(0 - z_{\text{PVF}})^2}$ / number of data points].

An increase in the index indicates worse stability, whereas a decrease in the index indicates improved stability.

PASW 18.0 was used to calculate means and standard deviations for the kinetic and kinematic variables, and to perform a one-way analysis of variance for the subject type. Statistically significant differences were subjected to post-hoc testing with Duncan's test. We used a statistical significance level of $\alpha = .05$ for all tests.

RESULTS

1. Results of leg stiffness and GRF variables

In sports activities and daily living, both legs are used for walking and running. Therefore, in this study, we evaluated lower-limb function using the mean of both legs.

Table 2 shows the results of the analysis of differences in leg stiffness and related variables upon landing according to ankle instability type. There were no large differences for PVF and loading rate, and the differences were not statistically significant ($p > .05$). Leg stiffness was significantly higher in the FAI group than in the NOR and ST groups ($p < .01$). The change in leg length was significantly lower in the FAI and ST groups than in the NOR group ($p < .001$).

2. Results of DPSI

Table 3 shows the results of the analysis of differences in the DPSI upon landing according to ankle instability type. There were no significant differences in MLSI, APSI, VSI, or DPSI ($p > .05$).

Table 2. Results of leg stiffness variables during vertical-drop landing

Section	Types of ankle instability			F	p-value	Post-hoc (Duncan)
	NOR (N)	FAI (F)	ST (S)			
Leg stiffness	13.37 ± 3.50	39.47 ± 21.17	29.65 ± 16.20	5.046	.018*	F > S > N
Peak vertical force (N/BW)	1.80 ± 0.15	1.89 ± 0.33	1.73 ± 0.40	0.435	.654	–
Leg length (%)	14.58 ± 3.84	6.13 ± 2.29	8.08 ± 2.92	14.350	.001***	F, S > N
Loading rate (N/BW/sec)	32.58 ± 9.77	33.51 ± 10.94	35.60 ± 17.97	0.093	.911	–

Note: $^{*}p < .05$, $^{***}p < .001$. NOR, normal; FAI, functional ankle instability; ST, surgical treatment

Table 3. Results of dynamic postural stability index during vertical-drop landing

Section	Types of ankle instability			F	p-value	Post-hoc (Duncan)
	NOR	FAI	ST			
Medial lateral stability index	0.94 ± 0.33	1.36 ± 0.38	1.08 ± 0.38	2.357	.123	–
Anterior-posterior stability index	1.89 ± 0.45	1.67 ± 0.38	1.55 ± 0.62	0.831	.452	–
Vertical stability index	17.42 ± 3.83	17.74 ± 4.71	18.90 ± 7.55	0.135	.875	–
Dynamic postural stability index	20.26 ± 4.08	20.77 ± 5.09	21.54 ± 8.19	0.079	.924	–

Note: NOR, normal; FAI, functional ankle instability; ST, surgical treatment

DISCUSSION

In previous studies evaluating lower-limb function in patients with FAI, it has been proposed that the impairment could be compensated by increasing dependence on the knee and hip joints, which also affect lower-limb function (Demeritt, Shultz, Docherty, Gansneder, & Perrin, 2002; Munn, Beard, Refshauge, & Lee, 2002; Worrell, Booher, & Hench, 1994). Delahunt et al. (2006) reported that ankle movement was restricted during landing in patients with FAI. As the body is a kinetic chain, restricted movement in one joint leads to compensatory action at other joints (Fry, Smith, & Schilling, 2003; Power, 2003). Thus, it has been reported that conservative treatment, such as rehabilitation therapy, taping, or bracing, can be effective for managing instability in patients with FAI, and allow preventing unnecessary surgery (Rodriguez-Merchan, 2012). However, ultimately, when normal lower-limb function cannot be restored, surgery is required. In our study, as landing is common during sports activities, we quantitatively evaluated lower-limb function in the FAI and ST groups during vertical-drop landing.

On the basis of the characteristics of lower-limb function in patients with FAI, we evaluated leg stiffness as an indicator of changes in total leg length and PVF. We found that the ST group had leg stiffness closer to the normal range than that of the FAI group. Although there was no difference in PVF, we believe that the difference in leg stiffness was related to the change in leg length (%). The NOR group showed an increased change in total leg length, whereas the FAI group showed the highest stiffness, which was considered to be related to the typical tendency toward restricted lower-limb movement (Demeritt et al., 2002; Delahunt et al., 2006; Munn et al., 2002; Worrell et al., 1994).

Although this mechanism can reduce dependence on the lateral ligament and simultaneously reduce the risk of ankle sprain, it also increases the dependence on the bones for shock absorption (Wright, Neptune, van den Bogert, & Nigg, 2000). In particular, as we observed in our study, the loading rate increased more in the FAI and ST groups than in the NOR group.

The loading rate, as a measure of the time taken for the force to increase up to the PVF upon landing (Diss, 2001), is the rate at which stress is applied to the tissues of the body (Cook, Farrell, Carey, Gibbs, & Wiger, 1997). In other words, a high loading rate results in poor shock absorption and a high level of stress applied to the lower limb in a short time (Hargrave, Carcia, Gansneder, & Shultz, 2003). Typically, an increase in the loading rate can cause patellofemoral pain and stress fractures (Cheung & Rainbow, 2014), and a loading rate of >100 N/kg/sec during running increases the risk of plantar fasciitis (Pohl, Hamill, & Davis, 2009).

In this regard, we believe that the increased leg stiffness in the FAI group was related to the increased loading rate. On the other hand, the ST group had to undergo a long period of rehabilitation to improve mechanical joint stability after surgery (Johnson & Johnson, 1993), and was expected to show shock absorption strategies depending on the type and duration of rehabilitation. This will need to be explored in future research. Thus, although a certain level of leg stiffness is required to maintain optimal athletic performance (Arampatzis et al., 1999; Dutto & Smith, 2002; Kerdok, Biewener, McMahon, Weyand, & Herr, 2002; Kuitunen, Komi, & Kyröläinen, 2002; McMahon & Cheng, 1990; Seyfarth, Geyer, Gunther & Blickhan, 2002; Stefanyshyn & Nigg, 1998), in patients with FAI, if repeated landing is performed without conservative treatment, failure to control leg stiffness could lead to sprain recurrence or secondary injury of the lower limb.

The integration of sensory information about position, including ankle joint movement, by the visual and vestibular systems can result in successful muscle contraction; however, impaired proprioception of the ankle ligaments can weaken reflexive muscle contraction to stabilize tremor (Ross et al., 2004). In this study, we used three-dimensional GRF values and time to stabilization to calculate the DPSI, and found that there were no significant differences between the NOR, FAI, and ST groups. This was thought to be related to a study showing that patients with FAI use strategies to minimize pressure on the joint structures when landing from a jump, but that a deficit in foot positional sense contributes to their impaired ability to offset the GRF (Konradsen et al., 1997; Thonnard et al., 1996).

The results of the present study can be summarized as follows. Leg stiffness was close to normal in the ST group. However, patients with FAI showed increased leg stiffness relative to impact force, and these mechanisms actually had a positive effect on dynamic postural stability. In particular, although impaired mechanoreceptor function due to ankle sprain could cause difficulties in protecting the ankle, ST can cause even more damage than the primary injury (Johnson & Johnson, 1993), and thus conservative treatment should be the first option (Rodriguez-Merchan, 2012). Thus, by analyzing potential differences in lower-limb function depending on the cause of ankle instability, we believe that it will be possible to evaluate ankle instability and design rehabilitation protocols based on the type of ankle injury.

CONCLUSION

The present study aimed to analyze the effects of FAI and surgery on postural stability and leg stiffness during vertical-drop landing. This study included a total of 21 adult male subjects (NOR: 7 persons, FAI: 7 persons, ST: 7 persons). We analyzed leg stiffness, kinetic variables (PVF, change in leg length, loading rate), and the DPSI (medial-lateral, anterior-posterior, vertical), and reached the following conclusions.

Leg stiffness was increased in the FAI group compared with the ST and NOR groups, and this was thought to be due to the change in leg length. Meanwhile, there were no significant differences between the groups in DPSI (MLSI, APSI, VSI, and DPSI) or loading rate. By testing these potential differences, we believe that it will be possible to evaluate ankle instability and design rehabilitation protocols based on the type of ankle injury.

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