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Evaluation of Resultant Ground Reaction Force and Its Velocity Using the Elapsed Time and Peak Reaction Force at 3-Dimensional Direction During Landing Task

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Abstract

The purpose of this study was to analyze the effects of bilateral landing leg and sex on resultant ground reaction force (GRF) and its velocity, using peak vertical GRF and elapsed time during drop landing tasks. A repeated-measures two-way analysis of variance explored the impact of landing legs and sex on the resultant vector, three-dimensional GRF, elapsed time, and velocity in 40 participants (20 males and 20 females). Participants performed drop landings from a 35-cm box. Effects of sex and landing leg were analyzed using a repeated-measures model (two sexes × two legs) on GRF magnitude and velocity. Females displayed shorter elapsed times to peak GRF compared to males in the anterior-posterior and vertical directions. Significant differences emerged between sexes in both magnitude and velocity of resultant and peak vertical GRF, with females exhibiting higher values. This suggests the adoption of distinct landing strategies between sexes. Notably, no significant differences were found in GRF magnitude or velocity between bilateral leg landings. These results indicate that healthy individuals of both sexes utilize different landing strategies during drop landings. This knowledge has potential applications in clinical settings for evaluating impulse force and stress transfer to the musculoskeletal system during landing tasks.

Key words: sex difference, resultant ground reaction force, resultant velocity, landing leg, 3-dimensional direction

Introduction

Landing motion is prerequisite motor skill in sports activities of basketball, football, volleyball and gymnastics etc… (Dufek & Bates, 1991; Hrysomallis, 2007; Kellis & Kouvelioti, 2009; Marshall et al., 2007; Niu et al., 2011). The motion was performed mainly in not only hurdle course of athlete but also military drill dangerous such as parachute landing (Amoroso et al., 1997; Decker et al., 2003; Gwinn et al., 2000; Johnson, 2003; Kernozek et al., 2005). The motion is applied to male and female in common, and then involved with ground reaction force (GRF) of different magnitude during jumping or landing (Yeow et al., 2009). Therefore the correlation between magnitude of GRF and injury possibility acceptable against body weight was published (Dufek & Bates, 1991; Frobell et al., 2008; Griffin et al., 2000; Johnson, 2003;

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Kirkendall & Garrett, 2000; Van der Harst et al., 2007), but was not yet cleared whether the difference by bilateral legs and sex in magnitude of GRF, its elapsed time, and velocity occurring from 3 direction (bilateral, anterior-posterior, vertical) was or not. In order to understand the mechanisms of typical sports injuries, such as anterior cruciate ligament injuries and ankle sprains, it is important to analyze GRF variables.

Landing motion causes furthermore large vertical GRF than that occurring during periodic motion as running or walking (Hyun & Ryew, 2018; Hyun et al., 2016; Zhang et al., 2008). Thus, vertical GRF is index signifying stress intensity on human system (McClay et al., 1994), and possibility of injury increases when muscular-skeletal system cannot accept the excessive stress (Devita & Skelly, 1992; Dufek et al., 1990; Gross & Nelson, 1988; Kovács et al., 1999). This danger, in a situation increasing the magnitude of loading rate due to impulse absorption and distribution may result in the greater danger potentially (Ricard & Veatch, 1990).

GRF occurring from lateral axis during initial phase of landing may increase stress on lateral ligament of ankle (Caulfield & Garrett, 2004). Particularly because monosynaptic reflex time of ankle was about 35-45 ms (0.035-0.04 sec), abnormal force occurrence within this time makes a reflection correction impossible in initial phase of between foot and ground contact (Garrett et al., 1999).

In addition, magnitude and variability of GRF in anterior-posterior direction has close correlation with danger of acute and chronic orthopedic injury (James et al., 2000; McLean et al., 2004). When anterior talofibular ligament (ATFL) of ankle was damaged or loosens, deceleration of center of gravity (COG) of body is impossible and thus increases the force variability in anterior-posterior direction through inducement of inefficient motor control (Safran et al., 1999). In previous studies, reduction of stability in anterior-posterior direction for patient with chronic ankle instability was verified (Brown et al., 2004; Ross & Guskiewicz, 2004).

Therefore, types of injury show different aspect according to properties frequency of GRF separated toward each direction, but GRF in three directions occurs at landing simultaneously. Furthermore, power of impulse signal in bilateral and anterior-posterior direction should not be ignored when considering potential role of shearing loading on tissue health (Turner et al., 2001). When considering in aspect of dynamics, the vector orientation of resultant GRF on joint center play a crucial role in the course of deciding direction and magnitude of moment acting on knee joint (Powers, 2010). Therefore, it may be improper to calculate variables related with impulse force only with independent frequency like impulse intensity and loading rate from vertical GRF against time function during landing (Gruber et al., 2017).

Thus, the purpose of this study was to analyze quantitatively the difference of magnitude and velocity using GRF variables in three directions occurring during drop landing. Assumption of this study was that resultant GRF and its velocity will be response sensitively against GRF of specific direction (medial-lateral, anterior-posterior, and vertical).

Material and Methods

Participants

Total 40 participants (total n=40, male=20, female=20) suitable for landing motion took part in voluntarily after agreement on the details of the experiment Table 1 and had no history of injury on muscular-skeletal system of vertebrae column and lower limb. All participants voluntarily agreed to participate and their movements were measured accordingly.

Table 1. *Demographics of the participants; values expressed as mean ± standard deviation (range)*

	Age (years)	Height (m)	Weight (kg)
Male	21.90±1.99	1.76±0.07	73.47±8.89
(n=20)	(20-27)	(1.69-1.97)	(60.74-94.25)
Female	20.80±1.47	1.61±0.05	59.59±8.79
(n=20)	(19-24)	(1.52-1.70)	(45.98-79.64)

Experimental Procedures

Limb dominance was tested by having the participant kick a soccer ball, with the kicking limb recorded as the dominant limb (right foot). Drop landing was taken off on the box of 35 cm height made of wood (Kamitani et al., 2023). Right or left foot was landed at random order on force platform (AMTI-OR-7, Advanced Mechanical Technology Inc., Watertown, MA, USA) to analyze the net effect of unilateral leg. All participants did enough warming-up and wore convenient training clothes. The participants were asked to minimize the landing impact in LAND, and they were also instructed to keep their hands on their hips and look at the forward marker during the tasks. However, they received no instruction regarding joint movements or how to absorb landing impact.

5 landings were performed on each leg, and only 1 successful trial was used for GRF analysis (considering real time data monitoring, success of impulse absorption, accurate landing on GRF plate, stabilized motion etc.). Data sampling of GRF was set at 1,000 Hz (Gain: 4 k, Voltage: 5 V) and recorded for 7 sec. per every trial. Also, considering the subjects' experimental progress and schedule, the landing experiment was conducted for 2 days under barefoot conditions without shoes.

Data Analysis

GRF (N) occurred from three directions (medial-lateral, anterior-posterior, vertical) were normalized (N/BW) by body weight (kg·N), and calculation of elapsed time was limited to maximal peak point.

Velocity of reaction force against each direction was divided with maximal peak value by elapsed time.

$$Medial-lateral\ rate = \frac{Peak\ medial-lateral\ force}{t}$$

$$Anterior-posterior\ rate = \frac{Peak\ anterior-posterior\ force}{t}$$

$$Loading\ rate = \frac{Peak\ veitical\ force}{t}$$

$$Resultant\ GRF\ velocity = \frac{\sqrt{(M-L)^2 + (A-P)^2 + (V)^2}}{t}$$

Thus, resultant vector was calculated with magnitude of GRF from three directions and vector component of velocity.

The average and the standard deviation on the calculated variables were obtained using PASW 21.0 program SPSS Inc., (Chicago, IL, USA), statistical significance difference among GRF variables by sex and landing legs during landing was verified by 2- way ANOVA at $\alpha < .05$.

Results

Peak Force and Elapsed Time

Summarized result on maximal GRF in bilateral, anterior-posterior, vertical direction and elapsed time to maximal peak value was as of Table 2. In Figure 1, elapsed time of bilateral direction did not show significant difference between main effects by sex and landing leg ($p > .05$). Elapsed time of anterior -posterior and vertical direction showed significant difference between main effects by sex and landing leg ($p > .05$), which followed more rapidness in female than that of male ($p < .001$).

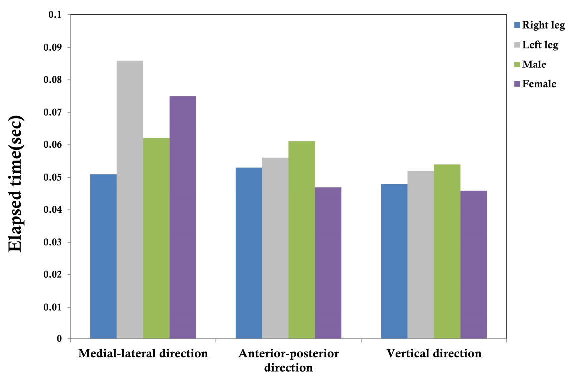

Figure 1. *Elapsed time to peak ground reaction force on three-dimensional directions during landing task*

Shear Force and Loading Rate

Maximal GRF of bilateral direction showed significant difference between main effects by sex and

Table 2. Results of peak force and elapsed time on three-dimensional directions during landing task

Section	Bilateral	Sex		Total average	Source	F	P
		Male	Female				
Elapsed time to peak medial-lateral force (sec)	Right leg	0.055±0.006	0.047±0.01	0.051±0.009	S	0.284	.595
	Left leg	0.07±0.059	0.102±0.198	0.086±0.145	B	2.245	.138
	Total average	0.062±0.042	0.075±0.141	0.068±0.104	S×B	0.738	.393
Elapsed time to peak anterior-posterior force (sec)	Right leg	0.061±0.029	0.046±0.01	0.053±0.023	S	8.419	.005**
	Left leg	0.062±0.028	0.049±0.009	0.056±0.022	B	0.251	.618
	Total average	0.061±0.028	0.047±0.01	0.054±0.022	S×B	0.039	.843
Elapsed time to peak vertical force (sec)	Right leg	0.052±0.006	0.044±0.01	0.048±0.009	S	15.159	.001***
	Left leg	0.055±0.01	0.049±0.006	0.052±0.009	B	3.603	.061
	Total average	0.054±0.008	0.046±0.008	0.05±0.009	S×B	0.323	.572
Peak medial-lateral force (N/BW)	Right leg	0.5±0.18	0.63±0.23	0.56±0.21	S	5.873	.018*
	Left leg	0.17±0.06	0.2±0.11	0.18±0.09	B	114.925	.001***
	Total average	0.33±0.21	0.42±0.28	0.37±0.25	S×B	1.928	.169
Peak anterior-posterior force (N/BW)	Right leg	0.51±0.22	0.61±0.35	0.56±0.29	S	0.227	.635
	Left leg	0.64±0.35	0.61±0.32	0.63±0.33	B	0.848	.360
	Total average	0.58±0.3	0.61±0.33	0.59±0.31	S×B	0.844	.361
Peak vertical force (N/BW)	Right leg	5.17±0.67	6.71±1.69	5.94±1.49	S	15.041	.001***
	Left leg	5.48±1.25	6.12±1.19	5.8±1.25	B	0.268	.606
	Total average	5.33±1	6.41±1.47	5.87±1.37	S×B	2.558	.114
Resultant ground reaction force (N/BW)	Right leg	5.22±0.68	6.77±1.70	6.00±1.50	S	14.666	.001***
	Left leg	5.52±1.27	6.15±1.21	5.83±1.26	B	0.329	.568
	Total average	5.37±1.01	6.46±1.49	5.92±1.38	S×B	2.576	.113

Values are presented as mean±standard deviation.
$^{***}p$<.001, $^{**}p$<.01, $^{*}p$<.05, BW: body weight: S: main effect of the sex, B: main effect of the bilateral leg, S×B: interaction

landing leg (p>.05). However, maximal GRF of anterior-posterior and vertical direction did not show significant difference between main effects by sex and landing leg (p>.05). In Figure 2, maximal GRF of vertical direction and resultant GRF showed significant difference between main effects by sex and landing leg, which followed more increased pattern in female than that of male (p<.001).

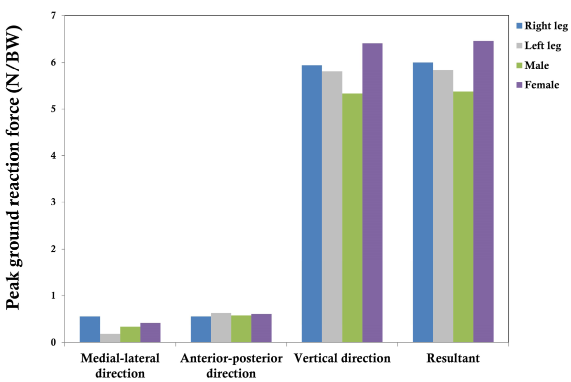

Figure 2. Peak ground reaction force on three-dimensional directions during landing task

Velocity applied to body by GRF during landing were as of Table 3 and Figure 3. Velocity of bilateral direction showed significant difference between main effects by sex and landing leg (p>.001). However, velocity of anterior-posterior direction did not show significant difference between main effects by sex and landing leg (p>.05). Loading rate and resultant GRF velocity showed significant difference between main effects by sex and landing leg, which followed more increased pattern in female than that of male (p<.001).

Table 3. *Results of shear and loading rate on three-dimensional directions during landing task*

Section	Bilateral	Sex		Total average	Source	*F*	*P*
		Male	Female				
Medial-lateral shear rate (N/BW/sec)	Right leg	9.26±4.03	14.38±7.44	11.82±6.45	*S*	11.343	.001***
	Left leg	3.54±2.4	9.16±11.24	6.35±8.51	*B*	11.739	.001***
	Total average	6.4±4.37	11.77±9.77	9.09±7.99	*S*×*B*	.024	.878
Anterior-posterior shear rate (N/BW/sec)	Right leg	9.45±4.73	16.26±18.07	12.86±13.48	*S*	2.391	.126
	Left leg	12.09±7.54	12.65±6.93	12.37±7.15	*B*	.042	.838
	Total average	10.77±6.35	14.45±13.63	12.61±10.73	*S*×*B*	1.723	.193
Loading rate (N/BW/sec)	Right leg	100.59±19.13	150.59±55.1	125.59±47.94	*S*	16.821	.001***
	Left leg	106.14±40.83	128.57±34.19	117.36±38.87	*B*	.868	.354
	Total average	103.36±31.6	139.58±46.61	121.47±43.56	*S*×*B*	2.437	.123
Resultant GRF velocity (N/BW/sec)	Right leg	101.55±19.55	152.82±56.55	127.19±49.17	*S*	17.087	.001***
	Left leg	107.01±41.25	130.09±34.45	118.55±39.29	*B*	.923	.340
	Total average	104.28±31.89	141.45±46.63	122.87±44.44	*S*×*B*	2.457	.121

Values are presented as mean±standard deviation.
***p<.001, BW: body weight, S: main effect of the sex, B: main effect of the bilateral leg, S×B: interaction

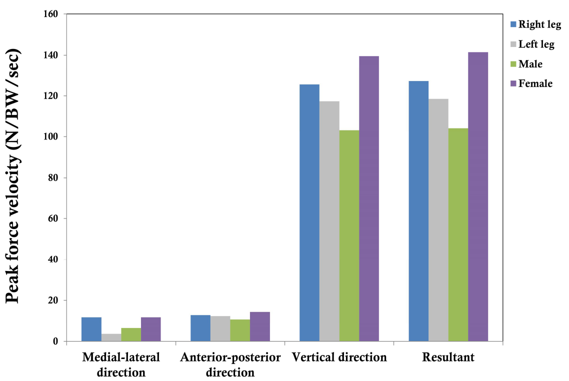

Figure 3. *Peak force velocity on three-dimensional directions during landing task*

Discussion

Apparent point appeared in the study is that occurrence time of maximal GRF by sex and landing leg showed significant difference between main effects, which influenced to velocity of GRF and thus followed difference of landing strategy between female and male (Colby et al., 2000; Lephart et al., 2002; Rozzi et al., 1999). When considering this difference, we need to heed that exercise physical activity and sports participating by both sex may be encountered frequent jumping and landing motion. Thus, fitness leader or clinician to enhance exercise efficiency should recognize an effect by sex and landing leg on GRF at landing.

Peak GRF from bilateral axis may cause an increased stress acting against lateral ligament (Caulfield & Garrett, 2004), and in particular because monosynaptic reflex time of ankle was about 35-45 ms (0.035-0.04 sec), abnormal force occurrence within this time makes a reflection correction impossible in initial phase of between foot and ground contact (Garrett et al., 1999). GRF occurred from 3 directions within elapsed time to maximal value of this study was similar with results of bilateral of 0,53 sec, anterior-posterior of 0.046 sec, and vertical force of 0.045 sec of healthy adult (Caulfield & Garrett, 2004). The participants of this study without functional, mechanical, chronic, and unstable condition showed 0.04 sec later from initial phase in appearance time of maximal shearing and impulse force, but female showed peak GRF within shorter time significantly than male.

Main effect by sex on integrated bilateral leg showed significant difference in maximal vertical GRF between 5.48 N/BW of male and 6.12 N/BW of female, and in resultant GRF of 5.52 N/BW, 6.46 N/BW respectively. Position of COG during landing may influence on direction of resultant GRF vector (Powers, 2010), and resultant GRF vector at knee extension generated at more proximity to axis of knee joint during landing (Podraza & White, 2010). In addition, direction of resultant GRF of this study may assume to be generated at more proximity to axis of knee joint in both sex, and therefore satisfied assumption of this study. Like this, it was needless to say that magnitude of vertical GRF due to landing direction and influence of gravity is more greatly generated than GRF vector of bilateral and anterior-posterior direction, but controllability acceptable the body weight of female may decrease, while increase stress on joint cartilage (Caulfield & Garrett, 2004).

While magnitude of medial-lateral GRF vector showed significant difference by sex and landing leg, variability of GRF in bilateral direction may be higher (Giakas & Baltzopoulos, 1997). High variability of bilateral GRF may influence on change of bilateral shearing velocity. A laterally-directed GRF vector would act to push the knee into valgus, increasing both knee abduction joint angle and moment–biomechanics implicated in injury at the joint (Creaby & Dixon, 2008). Therefore, this suggests that increasing GRF in a single direction may increase not only the size of the resultant GRF but also the risk of injury.

Shearing velocity against anterior-posterior direction by sex and landing leg did not show significant difference, but loading rate and velocity of resultant GRF showed significant difference as of 103.36 N/BW/sec, 139.58 N/BW/sec, and 104.28 N/BW/sec, 141.45 N/BW/sec of male and female respectively. Thus, it can be assumed that velocity of GRF reacted sensitively against change of magnitude and time.

Limitations of this study may be provided only information related motion of three dimensions on ankle and knee joint. Analysis recruited with 3D cinematography and GRF to predict possibility of injury danger related with clear stress level of joint and impulse force is necessary. Also further study included variables of joint moment of lower limb, power, angular displacement with resultant GRF component and its velocity will be necessary.

When summarizing the result, it was verified that magnitude of GRF and occurrence of velocity by landing leg in healthy adult did not show significant difference, but did influence to sex. Distributing strategy of GRF which adapts according to characteristics of sex and bilateral leg is necessary (Yeow et al., 2011), but it is necessary to heed on change of resultant GRF to solve a high variability against bilateral direction. This fact may be available to predict and calculate such motions of flexion/extension and adduction/abduction using only magnitude of resultant GRF and its direction.

Conflict of Interests

The authors have no financial or personal relationships with other people or organizations that have inappropriately influenced this research.

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