EFFECTS OF LANDING HEIGHT AND KNEE JOINT MUSCLE FATIGUE ON ANKLE AND KNEE JOINT KINEMATICS DURING CUTTING AFTER LANDING

YouKyung Kim and ChangHong Youm

Sport Biomechanics Laboratory, University of Dong-A, Busan, Korea

This study aimed to investigate the effects of landing height and knee joint muscle fatigue on ankle and knee joint kinematics during cutting after landing. Participants included 29 adults (age = 20.83 ± 1.56 years; height = 172.42 ± 9.51 cm; mass = 65.07 ± 10.18 kg) with no orthopedic history in the lower limb joints in the previous 6 months. The results showed that different landing heights of 30 and 40 cm and 30% fatigue of the peak torque of knee extensor found a forefoot landing and stiff landing strategy, when cutting after landing. These results might be due to a decline in the shock absorption capability of the knee joint and the movement capability related to cutting while increasing the contribution of the ankle joint.

KEY WORDS: fatigue, landing, cutting, kinematics, knee

INTRODUCTION: Muscle fatigue, an inevitable phenomenon that occurs in daily and sports activities, is defined as a decrease in the maximal force or power generation capability (Enoka & Duchateau, 2008; Lepers, Maffiuletti, Rochette, Brugniaux, Millet, 2002). Muscle fatigue negatively affects neuromuscular control, causing potentially dangerous movement strategies, and the accumulation of muscle fatigue becomes the direct cause of increased injury rates (McLean et al., 2007; Price, Hawkins, Hulse, & Hodson, 2004; Urabe et al., 2005). Hence, a study is needed that investigates the relationship between muscle fatigue and movement that quantifies fatigue levels (Fagenbaum & Darling, 2003; Gear, 2011; Harkins et al., 2005; Kellis & Koueliotí, 2009). Whether the index used in previous studies, 50% peak torque generated during maximum voluntary contraction, is appropriate due to its quick recovery rate and short fatigue effect is still being questioned and requires additional research.
Landing occurs during everyday life and is a common and essential motion during sports activities (Hrysomallis, 2007; Marshall, Covassin, Dick, Nassar, & Agel, 2007). Landing height, as a determinant external factor that determines landing form, is being extensively studied in relation to sports injuries (Ali, Robertson, & Rouhi, 2014; Yeow, Lee, & Goh, 2009, 2010). Although jump height and fatigue level are simultaneous factors, studies that consider the relationship between the two variables are lacking. Hence, the purpose of the current study was to investigate the effects that landing height and knee joint fatigue have on the kinematic variables of the ankle and knee joint during cutting after landing.

METHODS: Participants included 29 adults in their 20s (age = 20.83 ± 1.56 years; height = 172.42 ± 9.51 cm; mass = 65.07 ± 10.18 kg) with no orthopedic history in the lower limb joints in the previous 6 months. Nine infrared cameras (MX-T10; Vicon, UK) and one force plate (OR6-7; AMTI, USA) were used for the motion capture system and ground reaction force analysis. The sampling frequencies of the video data were set to 120 Hz and 1200 Hz for the force plate data, and the collected data were filtered by using 2nd order Butterworth low-pass filters at a cut-off frequency of 6 Hz (Decker, Torry, Wyland, Sterett, & Steadman, 2003; Pappas, Sheikhzadeh, Hagins, & Nordin, 2007).
All participants wore Spandex shirts and shorts and no shoes. The Plug in gait full body model modified from the Helen Hayes Marker Set consisted of twenty-six 14-mm spherical reflective markers. For the landing protocol, the participants first went on the 30- and 40-cm-high platforms, landed on the force plate by using their dominant lower limb at the signal, and then performed a side step with the non-dominant lower limb at a 45° angle. The arms were evenly extended and attached to the part behind and below the hip for landing, while the dominant lower limb was determined by using self-reporting and ball kicking tests (Kellis & Kouvelioti, 2009).

For maximum knee-extension peak torque measurement and fatigue inducement, the range of motion of the knee joint was set from extension angle 0° to flexion angle 90° with an angle speed of 60°/s by using an isokinetic dynamometer (Cybex; HUMACNORM, CSMI, USA). Termination of the fatigue protocol was considered when knee extension peak torque < 30% occurred ≥3 consecutive times (Fagenbaum & Darling, 2003). Nexus software (Vicon) was used for the collection, analysis, and synchronisation of the video and force plate data of landing in this experiment, and the data were analysed by averaging five successful landings prior to and after fatigue at each jumping height after the fatigue-inducing movements were made. Definitions of the events and phases were as followed: E1, the time when the landing foot initially made contact with the ground (threshold point, 10 N); E2, the maximum knee flexion point of the landing limb; and E3, the take-off point of the landing foot (threshold point, 10 N). P1 is E1–E2, while P2 is E2–E3.

The mean and deviation of each variable were calculated by using SPSS 20.0, and a two-way repeated-measure analysis of variance was performed of the interaction and main effect between the landing height and fatigue level with the level of significance was set at .05.

RESULTS: The results of the sagittal plane of the ankle joint angular position showed an interaction effect between landing height and fatigue ($F_{1, 28}$ = 4.632; p = .040) and a significant main effect between landing height ($F_{1, 28}$ = 22.891; p = .000) and fatigue ($F_{1, 28}$ = 28.093; p = .000) at E1 as well as a main effect between landing heights at E2 ($F_{1, 28}$ = 5.653; p = .024) and E3 ($F_{1, 28}$ = 4.408; p = .045) and a significant main effect between fatigue levels at E2 ($F_{1, 28}$ = 6.652; p = .015) and E3 ($F_{1, 28}$ = 4.443; p = .044) (table 1). The results of the frontal plane showed a significant main effect between landing heights at E1 ($F_{1, 28}$ = 8.333; p = .007), E2 ($F_{1, 28}$ = 7.567; p = .010), and E3 ($F_{1, 28}$ = 12.077; p = .002). The transverse plane results showed significant main effects between landing heights at E2 ($F_{1, 28}$ = 11.827; p = .002) and E3 ($F_{1, 28}$ = 5.299; p = .029) only. The sagittal plane results of the knee joint angular position showed a significant main effect between landing heights at E2 ($F_{1, 28}$ = 11.026; p = .003) and E3 ($F_{1, 28}$ = 7.446; p = .011) and a significant main effect between fatigue levels at E2 ($F_{1, 28}$ = 14.242; p = .001) and E3 ($F_{1, 28}$ = 7.461; p = .011) (table 2). The frontal plane results showed a significant main effect between fatigue levels at ($F_{1, 28}$ = 6.961; p = .013). The transverse plane results showed a significant main effect among landing heights at E1 ($F_{1, 28}$ = 6.230; p = .019), E2 ($F_{1, 28}$ = 10.178; p = .003), and E3 ($F_{1, 28}$ = 9.155; p = .005).The sagittal plane results of the ankle joint angular velocity showed an interaction effect between landing height and fatigue ($F_{1, 28}$ = 5.537; p = .026) and a significant main effect between landing heights ($F_{1, 28}$ = 17.472; p = .000) and fatigue levels ($F_{1, 28}$ = 37.491; p = .000) in P1 (table 3). P2 ($F_{1, 28}$ = 4.503; p = .043) showed significant main effects between fatigue levels. The frontal plane results showed a significant main effect between fatigue levels in P1 ($F_{1, 28}$ = 16.462; p = .000). The sagittal plane results of the knee joint angular velocity showed a significant main effect between landing heights in P1 ($F_{1, 28}$ = 6.137; p = .020) and a significant main effect between fatigue levels in P2 ($F_{1, 28}$ = 6.135; p = .020) (table 4). The frontal plane results showed an interaction effect between landing height and fatigue level in P1 ($F_{1, 28}$ = 4.659; p = .041) and a significant main effect between fatigue levels in P2 ($F_{1, 28}$ = 5.427; p = .027). The transverse plane results showed a significant main effect between fatigue levels in P1 ($F_{1, 28}$ = 6.674; p = .015) and P2 ($F_{1, 28}$ = 6.598; p = .016).

The sagittal plane results of the ankle joint range of motion showed an interaction effect between landing height and fatigue level ($F_{1, 28}$ = 5.509; p = .026) and a significant main effect between landing heights ($F_{1, 28}$ = 52.386; p = .000) and between fatigue levels ($F_{1, 28}$ = 57.762; p = .000), while the frontal plane results showed a significant main effect between fatigue levels ($F_{1, 28}$ = 7.505; p = .011) (table 5). The sagittal plane results of the knee joint range of motion showed a significant main effect between landing heights ($F_{1, 28}$ = 15.784; p = .000) and between fatigue levels ($F_{1, 28}$ = 7.293; p = .012), the frontal plane results showed significant main effect between fatigue levels ($F_{1, 28}$ = 13.613; p = .001), and the transverse plane results showed a significant main effect between landing heights ($F_{1, 28}$ = 8.561; p = .007) (table 6).

Table 1. The angular position of ankle joint through the events (Unit : °)

		Height	Pre	Post	*F*-value
Sagittal plane	E1	30 cm	-12.92±7.68	-17.50±8.08	22.891* (H)
		40 cm	-19.06±5.87	-21.20±7.77	28.093* (F)
					4.632* H×F)
	E2	30 cm	32.71±5.43	34.23±4.79	5.653* (H)
		40 cm	34.65±6.89	35.82±7.07	6.652* (F)
					0.330 (H×F)
	E3	30 cm	-2.60±6.61	-1.26±6.60	4.408* (H)
		40 cm	-0.68±6.97	1.54±8.13	4.443* (F)
					0.522 (H×F)
Frontal plane	E1	30 cm	-1.30±1.89	-1.36±1.81	8.333* (H)
		40 cm	-0.17±1.63	-0.32±1.90	2.341 (F)
					0.192 (H×F)
	E2	30 cm	1.69±1.13	1.79±1.43	7.567* (H)
		40 cm	2.66±1.85	2.94±1.79	3.761 (F)
					1.156 (H×F)
	E3	30 cm	-0.89±1.82	-0.85±1.76	12.077* (H)
		40 cm	0.25±1.82	0.64±2.11	3.795 (F)
					3.572 (H×F)
Transverse plane	E1	30 cm	6.04±10.25	6.18±9.99	3.879 (H)
		40 cm	0.99±12.85	1.96±12.84	1.648 (F)
					0.594 (H×F)
	E2	30 cm	-13.85±8.84	-12.88±9.01	11.827* (H)
		40 cm	-20.20±10.54	-19.39±10.17	3.607 (F)
					0.068 (H×F)
	E3	30 cm	2.62±11.09	2.43±10.36	5.299* (H)
		40 cm	-2.17±14.36	-4.24±14.91	3.004 (F)
					3.006 (H×F)

All data means m±sd, E1 is initial contact, E2 is maximum knee flexion, E3 is toe off, * is p<.05

Table 2. The angular position of knee joint through the events (Unit : °)

		Height	Pre	Post	*F*-value
Sagittal plane	E1	30 cm	12.89±6.77	12.38±6.68	0.041 (H)
		40 cm	12.14±5.20	12.66±6.59	0.000 (F)
					1.746 (H×F)
	E2	30 cm	51.14±6.10	48.12±7.25	11.026* (H)
		40 cm	55.48±7.43	52.06±8.30	14.242* (F)
					0.149 (H×F)
	E3	30 cm	17.27±6.72	18.60±5.08	7.446* (H)
		40 cm	19.78±7.12	22.48±6.55	7.461* (F)
					1.358 (H×F)
Frontal plane	E1	30 cm	0.34±3.94	0.61±3.41	0.065 (H)
		40 cm	0.33±4.47	0.31±4.96	0.453 (F)
					0.337 (H×F)
	E2	30 cm	-0.98±9.40	-1.47±7.75	0.236 (H)
		40 cm	-2.55±11.15	-2.13±10.42	0.009 (F)
					1.375 (H×F)
	E3	30 cm	-0.45±5.04	0.06±4.41	0.631 (H)
		40 cm	-1.33±5.11	-0.53±5.96	6.961* (F)
					0.276 (H×F)
Transverse plane	E1	30 cm	-4.81±7.60	-5.78±7.07	6.230* (H)
		40 cm	-0.11±8.57	-0.24±9.16	2.073 (F)
					1.281 (H×F)
	E2	30 cm	4.41±8.06	4.09±8.12	10.178* (H)
		40 cm	11.22±8.64	11.60±8.80	0.009 (F)
					1.804 (H×F)
	E3	30 cm	-3.30±7.15	-3.81±6.91	9.155* (H)
		40 cm	2.61±8.89	2.67±8.90	0.241 (F)
					0.577 (H×F)

All data means m±sd, E1 is initial contact, E2 is maximum knee flexion, E3 is toe off, * is p<.05

Table 3. The angular velocity of the ankle joint through the phases (Unit : °/s)

		Height	Pre	Post	*F*-value
Sagittal plane	P1	30 cm	257.31±62.24	316.99±64.89	17.472* (H)
		40 cm	296.70±59.43	335.97±73.31	37.491* (F)
					5.537* (H×F)
	P2	30 cm	-194.58±58.21	-217.97±38.39	0.194 (H)
		40 cm	-207.44±46.37	-212.49±40.02	4.503* (F)
					2.269 (H×F)
Frontal plane	P1	30 cm	17.05±9.33	19.30±9.42	0.105 (H)
		40 cm	15.61±8.35	19.51±10.74	16.462* (F)
					0.981 (H×F)
	P2	30 cm	-14.71±9.12	-16.06±8.71	0.452 (H)
		40 cm	-14.20±7.55	-14.20±8.94	0.871 (F)
					0.772 (H×F)
Transverse plane	P1	30 cm	-113.24±49.36	-117.00±44.42	1.336 (H)
		40 cm	-118.13±41.24	-126.67±45.78	2.227 (F)
					0.652 (H×F)
	P2	30 cm	93.86±42.56	93.85±35.64	0.393 (H)
		40 cm	104.21±34.64	91.93±42.66	4.053 (F)
					3.802 (H×F)

All data means m±sd, P1 is phase 1, P2 is phase 2, * is p<.05

Table 4. The angular velocity of the knee joint through the phases (Unit : °/s)

		Height	Pre	Post	*F*-value
Sagittal plane	P1	30 cm	214.94±43.17	217.64±40.88	6.137* (H)
		40 cm	236.68±43.26	226.40±43.39	0.481 (F)
					3.592 (H×F)
	P2	30 cm	-185.18±56.02	-180.06±25.77	3.759 (H)
		40 cm	-208.00±29.01	-181.42±28.79	6.135* (F)
					3.132 (H×F)
Frontal plane	P1	30 cm	-7.94±41.55	-13.39±38.53	0.095 (H)
		40 cm	-15.37±50.78	-12.88±44.14	0.770 (F)
					4.569* (H×F)
	P2	30 cm	4.10±35.05	11.47±32.31	0.006 (H)
		40 cm	5.80±45.77	8.27±36.50	5.427* (F)
					1.089 (H×F)
Transverse plane	P1	30 cm	53.03±28.85	60.54±29.01	4.077 (H)
		40 cm	62.70±27.80	69.39±35.57	6.674* (F)
					0.061 (H×F)
	P2	30 cm	-43.67±25.26	-49.78±22.47	3.011 (H)
		40 cm	-50.81±27.25	-57.09±28.03	6.598* (F)
					0.003 (H×F)

All data means m±sd, P1 is phase 1, P2 is phase 2, * is p<.05

Table 5. Range of motion of ankle through shock absorption phases (Unit : °)

	Height	Pre	Post	*F*-value
Sagittal plane	30 cm	48.12±7.76	54.18±7.92	52.386* (H)
	40 cm	55.79±7.32	59.30±8.38	57.762* (F)
				5.509* (H×F)
Frontal plane	30 cm	3.32±1.52	3.43±1.52	0.001 (H)
	40 cm	3.16±1.45	3.56±1.64	7.505* (F)
				1.310 (H×F)
Transverse plane	30 cm	21.98±6.94	20.69±6.19	4.015 (H)
	40 cm	23.41±5.50	23.39±6.35	2.912 (F)
				2.944 (H×F)

All data means m±sd, * is *p<.05*

Table 6. Range of motion of knee through shock absorption phases (Unit : °)

	Height	Pre	Post	*F*-value
Sagittal plane	30 cm	40.96±5.06	39.24±5.57	15.784* (H)
	40 cm	45.04±6.37	42.33±7.65	7.293* (F)
				0.696 (H×F)
Frontal plane	30 cm	7.86±3.66	6.54±3.82	2.968 (H)
	40 cm	9.64±4.65	8.48±3.62	13.613* (F)
				0.073 (H×F)
Transverse plane	30 cm	10.61±4.17	11.26±4.05	8.561* (H)
	40 cm	12.88±4.51	13.39±5.79	2.635 (F)
				0.053 (H×F)

All data means m±sd, * is *p<.05*

DISCUSSION: All participants showed a landing strategy of forefoot landing and a stiff landing. According to the sagittal plane results of the ankle joint angular position, as the landing height increased, the angular position of plantar flexion at E1, the angular position of dorsiflexion at E2, and the angular position of plantar flexion at E3 also increased. According to the frontal plane results, as the landing height increased, the angular position of eversion decreased at E1, the angular position of inversion increased at E2, and converted from

eversion to inversion at E3. According to the transverse plant results, as the landing height increased, the angular position of external rotation increased at E2 and the angular position of internal rotation converted to the angular position of external rotation at E3. According to the sagittal plane results of the ankle joint angular velocity and the maximum range of motion of the knee joint, in the shock absorption in P1, it increased as the landing height increased. Such results following the increase in landing height leads to overloaded ankle joints, which may increase injury rates. A total of 85% of such ankle joint-related injuries occur in the lateral side, and they are mainly caused by excessive inversion of the ankle joint (Gutierrez, Jackson, Dorr, Margiotta, & Kaminski, 2007). According to the sagittal plane results of the knee joint angular position, as the landing height increased, the angular position of flexion increases appeared at E2 and E3. According to the transverse plane results, the angular position of external rotation decreased at E1, the angular position of internal rotation increased at E2, and the external rotation converted to internal rotation at E3. The maximum range of motion of the sagittal and transverse planes and sagittal plane angular velocity of the knee joint increased as the landing height increased in P1. A knee joint flexion increase due to a landing height increase can result in excessive flexion-related damage (Yeow et al., 2010; Ali et al., 2014).
According to the sagittal plane results of the ankle joint angular position, after fatigue, the angular position of plantar flexion increased at E1, the angular position of dorsiflexion increased at E2, and plantar flexion converted to dorsiflexion at E3. The angular velocity and maximum range of motion of the sagittal and frontal planes of the ankle joint increased in P1 after fatigue. Unlike the aforementioned ankle joint results according to landing height increase, there was a significant difference in the results of both the sagittal plane and the frontal plane. This is similar to the results of Madigan & Pidcoe (2003), who reported that, although the range of motion of the knee and hip joints decrease during single-leg landings, the range of motion of the ankle joint increased. Further, if a landing is performed under an accumulated fatigue condition, overload on the ankle joint will increase further (Weinhandl, Smith, & Dugan, 2011). According to the sagittal plane results of the knee joint angular positions, after fatigue, the angular position of flexion decreases at E2 and the angular position of flexion increases at E3. According to the knee joint angular velocity results, in the sagittal plane, an extension angular velocity decrease occurred in P2, while the abduction angular velocity increased in P2 after fatigue for the frontal plane, increased internal rotation angular velocity in P1, and increased external rotation angular velocity in P3 for the transverse plane. The maximum range of motion of the sagittal and frontal planes of the knee joint decreased after fatigue. The knee joint fatigue seen in the present study negatively affects shock absorption capabilities and direction change-related movement capabilities, and these results are thought to contribute to increased knee joint injury rates.

CONCLUSION: The different landing heights of 30 and 40 cm and 30% fatigue of the peak torque of knee extensor resulted in a forefoot landing and stiff landing strategy during cutting after landing. These results might decrease the shock absorption capability of the knee joint and the movement capability related to cutting but increase the contribution of the ankle joint.

REFERENCES:

Ali, N., Robertson, D. G. E., & Rouhi, G. (2014). Sagittal plane body kinematics and kinetics during single-leg landing from increasing vertical heights and horizontal distances: Implications for risk of non-contact ACL injury. *The Knee, 21*, 38-46.

Gutierrez, G. M., Jackson, N. D., Dorr, K. A., Margiotta, S. E., & Kaminski, T. W. (2007). Effect of fatigue on neuromuscular function at the ankle. *Journal of Sport Rehabilitation, 16(4),* 295.

Madigan, M. L., & Pidcoe, P. E. (2003). Changes in landing biomechanics during a fatiguing landing activity. *Journal of Electromyography and Kinesiology, 13(5),* 491-498.

Weinhandl, J. T., Smith, J. D., & Dugan, E. L. (2011). The effects of repetitive drop jumps on impact phase joint kinematics and kinetics. *Journal of Applied Biomechanics, 27(2)*, 108-115

Yeow, C. H., Lee, P. V. S., & Goh, J. C. H. (2010). Sagittal knee joint kinematics and energetics in response to different landing heights and techniques. *The Knee, 17(2),* 127-131.