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原著論文

Motion Analysis of Impact Absorption during Jumping : A Comparative Study of Verbal Instructions in Healthy Young Adults

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ジャンプ中の衝撃吸収の動作分析：健康な若年成人における口頭指示の比較研究

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要約

ジャンプ着地時の外傷予防を念頭に、若年被験者16名に対して３次元動作解析装置および床反力計を用いて、各人の最大努力で床からの鉛直ジャンプを、① 特に指示なし、② 口頭でできるだけソフトに着地するように指示、の２つの課題を行わせた。結果、両者のジャンプ高さに差はなく、②は①に比べ、床反力（垂直成分）の値が著明に小さく、空中での脚の曲げ開始が早期で、着地時の地面衝突時間と着地時間は長かった。

Keywords: landing, ground reaction forces, impact absorption, verbal instructions, biomechanics.

1．Introduction

A large impact force is transmitted to the body during jumping and landing, which may cause lower-extremity injuries[1)-3)]. The most common injuries occur in the knee and ankle ligaments and are directly related to the joint angles and moments (i.e., torque or joint loading) at the hip, ankle, and knee joints[4)]. For example, the risk of anterior cruciate ligament (ACL) injury can increase during landing under greater impact loads[5)]. If the impact force exceeds the force produced by the involved musculature, all exceeding ground reaction forces are diverted by the bones and ligamentous tissue, amplifying the expected risk of ligament ruptures[6)]. This injury mechanism is particularly prevalent in the female population[7)]. The ground reaction forces produced during jumping and landing are an accurate representation of impact intensity, and there is an association between the impact force and compressive strain on the bones and the surrounding musculature[8)]. Studies in which, jump-landing impact forces are expressed relative to body weight (BW), have reported these forces to be as high as 5.7–8.9 times the BW, during specific sporting movements[9-11).] Jump- landing forces are frequently observed in sports such as basketball and volleyball. [10, 12)]. The stiffer jump-landing technique is a risk factor for overuse and acute injuries[13)].

Several studies have shown that some feedback methods effectively reduce the peak vertical forces during landing. Prapavessis et al. reported that individuals who receive augmented feedback can assimilate precise instructions related to the modification of lower limb kinematics and lower their ground reaction forces in an effective, immediate way[14]. Oñate et al. showed that high-impact landing forces can be reduced by implementing augmented feedback information that instructs individuals on how to land properly[15]. Data published from McNair et al. suggested that precise instructions related to the kinematics of the lower limbs can lead to a 13% decrease in peak ground reaction forces[16]. Landing is an essential task used in several sports. Cronin et al. reported that augmented feedback significantly decreased the vertical ground reaction force by 23.6%[9]. Additionally, Oñate et al. showed that self-feedback or combined videotape feedback was the most useful for increasing knee angular displacement flexion angles and reducing peak vertical forces during landing[17], while Eriksen et al. concluded that a combination of expert-provided and self-analysis feedback produced the greatest decrease in the peak vertical ground reaction force during a jump landing task[18]. Finally, Ericksen et al. provided evidence of the acquisition of biomechanical changes in jump landing following a 4-week feedback intervention that integrated both traditional and real-time feedback mechanisms[19].

We suggest that such feedback effectively increases individual awareness, leading to softer landings. However, few studies have reported on the differences in human kinematic motion with and without verbal instructions regarding shock absorption during landing. Moreover, how human movements change while landing after receiving instruction remains unclear. Therefore, in this study, we aimed to characterize human motion with and without verbal instructions for shock absorption during landing. According to the law of conservation of mechanical energy, if air resistance is ignored, the velocity at which an object falling from a certain height hits the ground is determined by the formula $v = \sqrt{2gh}$ (v: velocity (m/s); g: acceleration due to gravity ≒ 9.8 (m/s^2); and h: jump height (m)). The momentum at the time of ground landing is determined by the mass and jump height, while it is constant for a given height. In other words, if there was no difference in jump height between landing with and without verbal instructions, the momentum at the time of landing would be the same. In addition, because the changes in momentum and impulse are equal, a decrease in the ground reaction force, due to verbal instructions, implies a longer collision time; moreover, both impact times can be roughly calculated. By identifying the start and end time of the foot and floor impacts during landing, physical forces can be replaced by kinematic comparisons, such as time, rather than kinetic comparisons. As a result, it is expected that it will be possible to conduct mechanical studies to a certain extent using simple tools such as observation, video cameras, tape measures, and stopwatches, in a field where there are no force plates. Second in this study, we compared the characteristics of body movements in the air before landing, with and without verbal instructions, focusing on the timing of the start of lower limb bending. Therefore, we considered extracting movement characteristics by comparing the differences in leg flexion timing and leg length, at the time of landing, with and without verbal instructions.

2. Methods

2.1. Participants

We enrolled 16 healthy young adults in this study (Table 1).

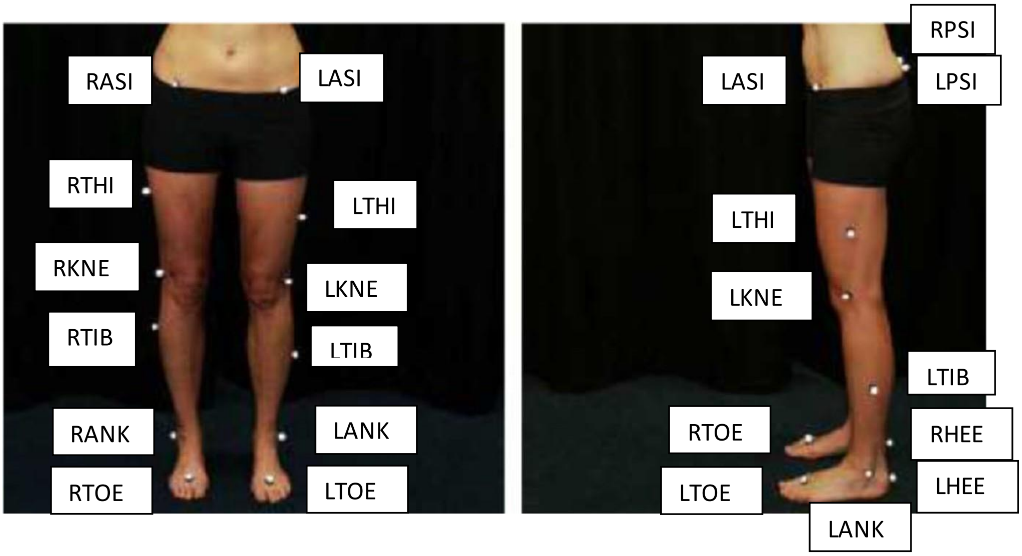
Table 1. Subject description

	16 participants	9 females	7 males
Height (m)	1.69 ± 0.09	1.62 ± 0.04	1.78 ± 0.05
SMD (m)	0.87 ± 0.05	0.84 ± 0.03	0.88 ± 0.05
Weight (kg)	58.8 ± 7.3	53.9 ± 4.0	65.2 ± 5.2

SMD: spinomallaolous distance
Fugures expressed as mean ± SD

2.2. Procedure

Sixteen reflective body markers (Vicon Plug-in Gait lower body model) were used for each participant. A three-dimensional motion analysis system (Vicon



Vicon® Plug-in Gait lower body model (16 points)	
Pervis	LASI: Left anterior superior iliac spine
	RASI: Right anterior superior iliac spine
	LPSI: Left posterior superior iliac spine
	RPSI: Right posterior superior iliac spine
Thai	LTHI: Left thigh
	RTHI: Right thigh
Knee	LKNE: Left Knee
	RKNE: Right knee
Shin	LTIB: Left tibia
	RTIB: Right tibia
Foot	LANK: Left lateral malleolus
	RANK: Right lateral malleolus
	RTOE: Right second metatarsal
	LTOE: Left second metatarsal
	RHEE: Right heel
	LHEE: Left heel

Figure 1. Sixteen reflective body markers (Vicon Plug-in Gait lower body model) were applied to each participant.

Nexus 2.5, Oxford, UK; Sampling frequency: 100 Hz, seven capture cameras) and a force plate (Z15907A, Kistler, Novi, MI, USA; Sampling frequency: 1,000Hz) were used during the jumps (Figure 1).

The participant stood barefoot, with the right leg on the force plate.

In the first trial, each participant jumped vertically with maximum effort, without verbal instructions on shock absorption. In the second trial, we instructed each participant on how to maximize their efforts while jumping, similar to the first trial, and how to land softly while being aware of the shock absorption. A second trial was conducted immediately after the first one (Figure 2).

2.3. Data analysis

2.3.1 Detailed analysis of the timing of each phase of the landing motion

Changes in jump height, landing time, vertical ground reaction force, and extended leg length (between the right side of the anterior superior iliac spine (ASIS) and the lateral malleolus) were measured while landing with and without verbal instructions on shock absorption. The jump height and fall velocity of the participants were calculated from the trajectory of the right ASIS marker. Furthermore, the potential energy at the highest jump height (J) was calculated as mass (**m**) (kg) × acceleration due to gravity (g) (≒ 9.8) (m/s^2) × height (**h**) (m), assuming that the participant has no kinetic energy at this height. The kinetic energy at landing (J) was calculated as $\frac{1}{2}$ × mass (m) (kg) × [velocity (V) (m/s)]^2, while the potential energy was zero at this point. Because both the kinetic and potential energies are equal, according to the law of conservation of mechanical energy, the fall velocity can be theoretically estimated using the equation $v = \sqrt{2gh}$, assuming that there is no air resistance. This was calculated for confirmation, while the correlation coefficient between the two conditions was calculated.

The root mean square of the vertical ground force amplitude during landing was calculated with and without verbal instructions. To compare these differences, the maximum ($F_{(z)max}$) and average ($F_{(z)avg}$) values were calculated. For the $F_{(z)avg}$ values extracted, the calculated ranged from the initial landing time at the maximum fall velocity of the right ASIS marker to the lowest terminal landing time.

Given that the force plate measures concern only the right leg, the change in momentum (Δp) from the initial landing time (mV_i) to the terminal landing time (mV_t) was calculated as [mass (1/2 of body weight) (m) (kg) × vertical fall velocity at the terminal landing (V_t) (m/s)] – [mass (1/2 of body weight) (m) (kg) × vertical fall velocity at the initial landing (V_i) (m/s)]. V_t was estimated to be zero.

$$\Delta p = mV_t - mV_i$$

Based on the principle of superposition, the force applied to the right leg can be considered to be the resultant force of the downward force due to gravitational acceleration applied to 1/2 of the body weight ($F_{(z)mg}$) and the upward force due to the ground reaction force ($F_{(z)}$). $F_{(z)mg}$ was extracted from the ground reaction force data while the participant stood at rest. Impulse at landing (J) was estimated using the formula: average of the vertical resultant force ($F_{(Z)avg} - F_{(z)mg}$) (N) × the duration time of collision (Δt) (S).

$$J = (F_{(Z)avg} - F_{(z)mg})\ \Delta t$$

The change in an object's momentum is equal to the impulse on the object (linear momentum–impulse theorem) [20].

$$\Delta p = J$$

For jumping conditions with and without verbal instructions, the duration of the ground collision during landing (Δt) was calculated as follows:

$$\Delta t = \Delta p\ /\ (F_{(Z)avg} - F_{(z)mg})$$

To compare the differences in body movements in space before landing, we extracted the time from the highest point of the jump to the starting point of leg flexion. In this study, we focused on the entire length of the lower limb, individual compound movements of the hip, knee, and ankle joints make up the lower limb during landing. Given that leg length changes during jumping, we determined the onset of leg flexion as the time corresponding to the extreme value obtained from the second derivative of the right leg length (L) with respect to time ($\frac{d^2L}{dt^2}$). (Figure 3)

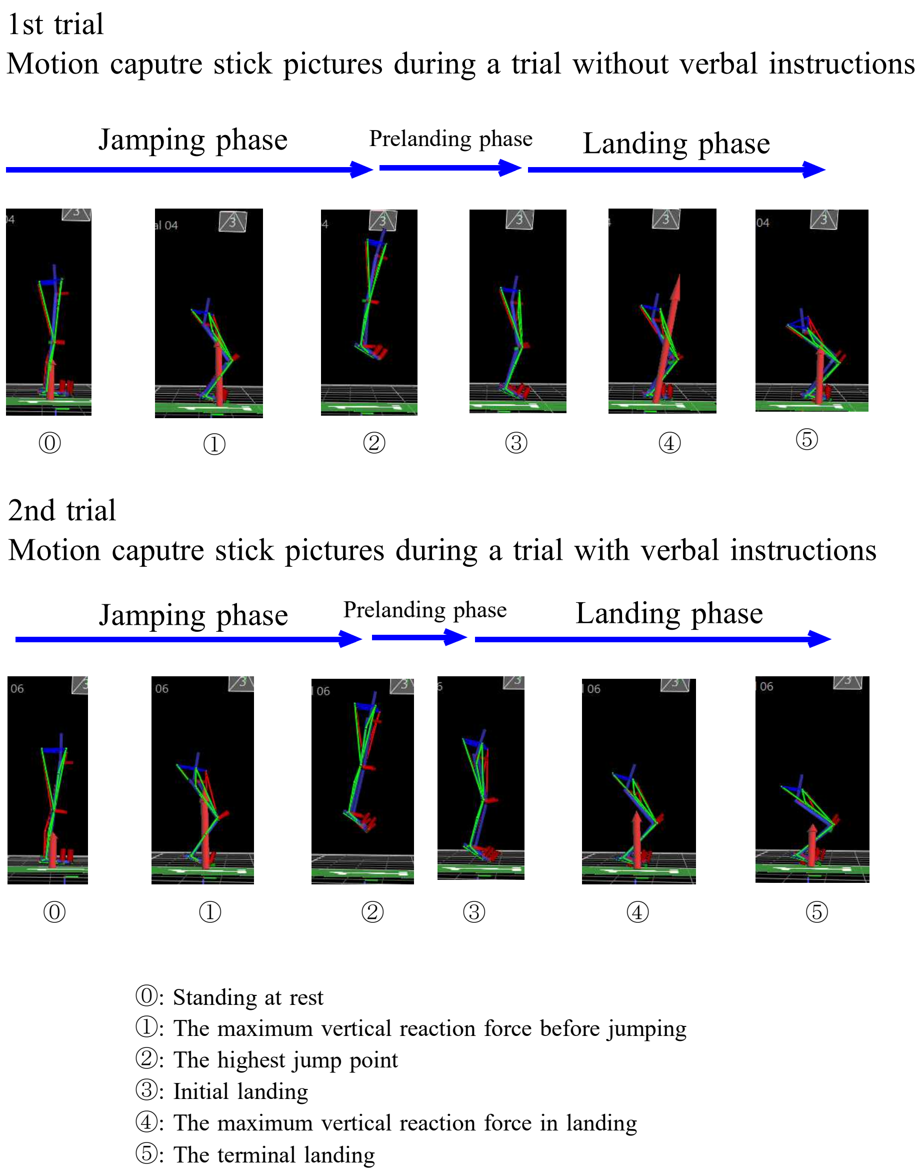


Figure 2. A trial representation of a participant with and without verbal instructions

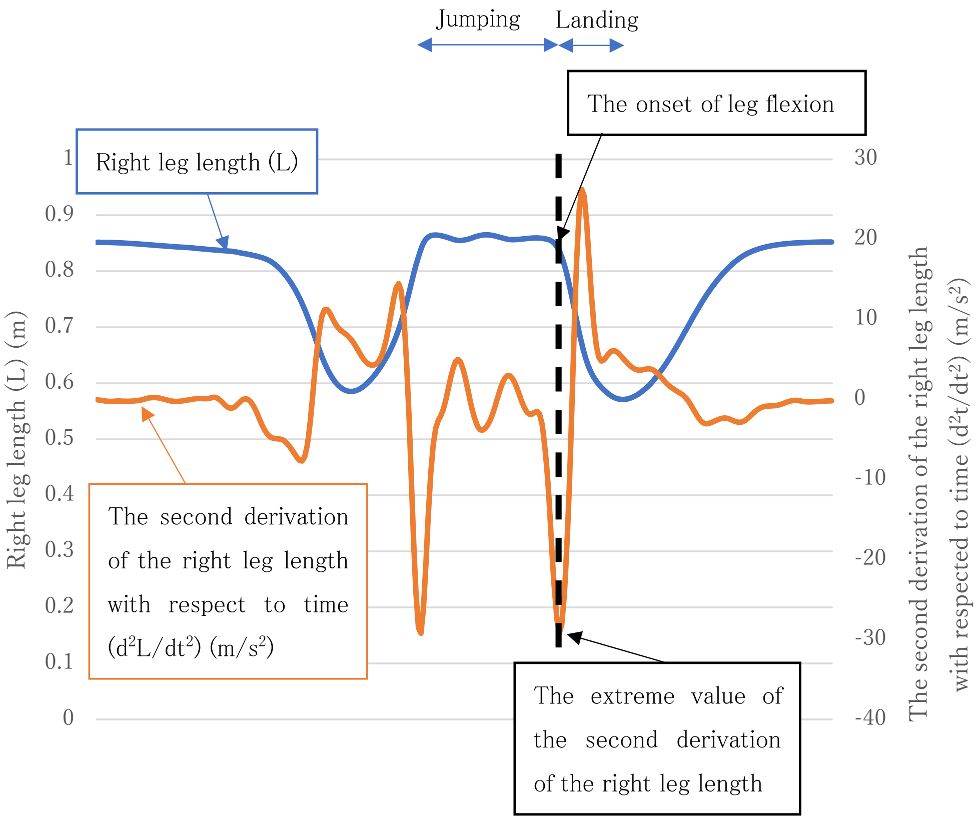


Figure 3. Determination of the onset of leg flexion

We considered the prelanding phase from the starting point of leg flexion after the highest point of the jump to the time when the fall velocity of the right ASIS marker was at its maximum, that is, the initial landing time. We considered the landing phase from the initial landing time to the time when the height of the right ASIS marker was the lowest (the terminal landing time).

To compare the extent to which the right leg decreased during the landing or prelanding phases with and without verbal instructions, the leg length decrease ratio was calculated with and without verbal instructions. This was defined as using the following formula: ([shortened right leg length during each phase] / [right leg length in the standing position]) × 100(%).

2.3.2 Comparison of joint range, joint angular velocity, and joint angular acceleration in the lower extremities during landing

To clarify the kinematic characteristics of joint motions (hip, knee, and ankle) during landing with and without instructions, the joint range, angular velocity, and angular acceleration during landing were measured using a three-dimensional motion analysis system.

Data were analyzed using the t-test and Wilcoxon signed-rank test at a significance p value of 5%. Statistical analysis was performed using JMP Pro 17.1.0 (SAS Institute, Cary, North Carolina, USA), a statistical analysis software.

2.4. Ethical approval

This study complied with the tenets of the Declaration of Helsinki and the ethical guidelines related to medical studies, as stipulated by current Japanese law. Proper consideration was given to the protection of the participants' data, and a description of ethical considerations, such as explanations and informed consent, was provided. This study was approved by the Ethics Committee of the Teikyo Heisei University (approval no. R01-078). The experimental conditions were explained to the participants, and written consent was obtained from them. The authors declare no conflicts of interest. Permission for publication of results was obtained from all the participants.

3. Results

3.1. Analysis of the timing of each phase of the landing motion

The results are shown in Table 2.

3.1.1. Jump height

The jump height was not significantly different between jumping with and without verbal instructions in either female or male participants.

3.1.2. The maximum fall velocity

Maximum fall velocity was not significantly different between jumping with and without verbal instructions.

The fall velocity relationship was used to calculate the right ASIS marker trajectories (V_1), using the law of conservation of mechanical energy (V_2), was as follows:

$V_1 = 0.86V_2 + 0.25$ (without instructions) ($p<0.001$)

$V_1 = 0.84V_2 + 0.31$ (with instructions) ($p<0.001$)

3.1.3. Vertical ground reaction force and time durations

With verbal instructions, both the maximum vertical ground reaction force ($F_{(z)max}$) and the average of the vertical resultant force ($F_{(z)avg} - F_{(z)mg}$), were significantly lower than those without verbal instructions.

The duration from the highest jumping point time to the leg flexion start time with verbal instructions was shorter than that without verbal instructions. The prelanding phase duration was significantly longer when jumping with verbal instructions than when jumping without verbal instructions. In some cases, when jumping without verbal instructions, there was no prelanding phase; consequently, the legs did not flex before landing. The landing phase was significantly longer when jumping with verbal instructions, along with longer time durations, compared with those observed when jumping without verbal instructions.

3.1.4. Duration of the ground collision in landing (Δt)

The duration of the ground collision during landing with verbal instructions (Δt_1) was significantly longer than that without verbal instructions (Δt_2).

The duration of the ground collision during landing (Δt) and the landing phase (Lt) were almost similar. The duration of the ground collision during landing with (Δt_1)and without (Δt_2) verbal instructions was calculated using the landing phase time with (Lt_1) and without (Lt_2) instructions, respectively, as follows:

$\Delta t_1 = 0.75\,Lt_1 + 0.05$ (without verbal instructions) ($p=0.0011$)

$\Delta t_2 = 0.97\,Lt_2 + 0.07$ (with verbal instructions) ($p= 0.0042$)

3.1.5. Leg length decrease ratio

The right leg length decrease ratio with verbal instructions was significantly greater than that without verbal instructions in both the prelanding and landing phases. Each participant underwent a prelanding phase while jumping with verbal instructions. However, some individuals who did not receive verbal instructions did not bend their legs before the landing phase. Thus in this study, these ratios were regarded as zero.

3.2 Comparison of angular range, joint angular velocity, and acceleration in the lower extremities during landing

The results are displayed in Table 3.

Table 2. Summary of results

	Without verbal instructions	With verbal instructions	
Jump height (m)			
# Participants	0.44 (0.06)	0.42 (0.06)	
# Females	0.36 (0.04)	0.36 (0.04)	
# Males	0.48 (0.02)	0.45 (0.02)	
Maximum fall velocity (m/s)			
# Calculated by the right ASIS trajectory	2.70 (0.17)	2.68 (0.19)	
# Calculated by law of conservation of energy	2.93 (0.21)	2.84 (0.22)	
Time duration (s)			
# From the highest jumping point time to the leg flexion start time	0.29 (0.03)	0.26 (0.03)	*
# **Prelanding phase** [1]	0.00 (0.01)	0.02 (0.01)	*
# Landing phase [2]	0.21 (0.07)	0.32 (0.04)	*
# $F_{(z)max}$; Maximum vertical ground reaction force (root mean square value) (N)	790.02 (177.19)	610.75 (88.57)	*
♭ Average of the vertical resultant force in landing (N) [3]	403.92 (151.20)	226.13 (85.34)	*
# Δp; Change in momentum during landing phase (kg m/s)	76.75 (13.43)	78.35 (12.78)	
♭ Δt; Duration of the ground collision in landing [4] (s)	0.23 (0.10)	0.40 (0.16)	*
Right leg length decrease ratio [5] (%)			
# **Prelanding phase**	2.50 (0.90)	5.70 (2.10)	*
# Landing phase	26.00 (4.50)	40.20 (10.00)	*

* P.<0.05

The numerical value is expressed as median (quartile deviation). Statistical analysis was performed using the Wilcoxon signed-rank test.

♭ The numerical value is expressed as mean (standard deviation). Statistical analysis was performed using the t-test.

[1] Prelanding phase regarded as a time from the leg flexion start time to the right ASIS marker maximum vertical fall velocity time, i.e., initial landing time.
2 Landing phase regarded as a time from the initial landing time to the terminal landing time. Initial landing time is defined as the time when the right ASIS marker's fall velocity was the maximum. Terminal landing time is defined as the time when the right ASIS marker's height was the lowest.
[3] Average of the vertical resultant force in landing was calculated by ($F_{(z)Avg}$ - $F_{(z)mg}$).
[4] Duration of the ground collision in landing (Δt) was calculated by Δp / ($F_{(Z)Avg}$ - $F_{(z)mg}$) .
[5] Right leg length decrease ratio was calculated by [(Right leg shortened length during each phase)/(Right leg length during standing position)] × 100(%).

Table 3. Angular range, maximum angular velocity, and maximum angular acceleration of the lower extremities while landing

	Without verbal instructions	With verbal instructions	
Motion direction	Angular range (deg)	Angular range (deg)	
Hip joint			
flexion	55.30 (11.6)	77.40 (14.65)	*
abduction	1.75(7.55)	7.70(7.89)	
Internal rotation	14.90(5.07)	24.00(6.14)	*
Knee joint			
flexion	85.15(7.05)	113.45(14.03)	*
varus	24.35(10.80)	25.85(10.54)	*
Internal rotation	29.40(3.65)	40.90(10.05)	*
Ankle joint			
dorsi flexion	33.45(4.26)	34.3(6.30)	
inversion	3.85(1.51)	3.40(1.50)	
external rotation	23.35(9.85)	18.00(7.09)	
	Maximum angular velocity (deg/s)	Maximum angular velocity (deg/s)	
Hip joint			
flexion	312.25(42.48)	332.65(23.23)	
abduction	15.00(51.64)	21.90(46.97)	*
Internal rotation	118.30(48.22)	109.00(39.49)	
Knee joint			
flexion	545.90(37.08)	587.20(38.35)	
varus	198.70(58.98)	204.50(72.55)	
Internal rotation	192.35(54.31)	231.34(44.60)	
Ankle joint			
dorsi flexion	641.15(116.36)	524.35(69.75)	*
inversion	36.95(12.34)	22.75(7.98)	*
external rotation	209.25(69.54)	131.90(55.98)	*
	Maximum angular acceleration (deg/s^2)	Maximum angular acceleration (deg/s^2)	
Hip joint			
extension	3911.50(987.41)	3687.70(802.01)	
adduction	1111.90(880.39)	524.90(523.95)	*
external rotation	1460.80(773.68)	1297.90(537.12)	
Knee joint			
extension	6635.65(1585.84)	5002.8(613.55)	*
valgus	2762.20(1748.17)	2221.7(932.54)	
external rotation	2649.80(1499.61)	2221.7(932.54)	
Ankle joint			
planta flexion	11144.85(3721.86)	8650.95(1646.85)	*
eversion	583.00(270.90)	441.70(145.45)	*
internal rotation	3711.80(1123.65)	2422.10(867.59)	*

The numerical value is expressed as median (quartile deviation). Statistical analysis was performed using the Wilcoxon signed-rank test.

* P<0.05

3.2.1. Angular range

The range of motion of the hip joint was greater with instructions for flexion and internal rotation than without instructions. During landing, we observed both adducted and abducted their hip joints. The range of motion of the knee joint was greater with instructions for flexion, adduction, and internal rotation than without instructions. There was no difference in the range of motion of the ankle joint between those with and without instructions.

3.2.2. Maximum angular velocity

There was no difference in the maximum angular velocities of the hip and ankle joints between those with and without instructions. The maximum angular velocity of the ankle joint increased with instructions for dorsiflexion, inversion, and external rotation, as opposed to that without instructions.

3.2.3. Maximum angular acceleration

The maximum angular acceleration of knee extension with instructions was lower than that without instructions. The maximum angular acceleration of ankle plantar flexion, eversion, and internal rotation with instructions was inferior to that without instructions.

4. Discussion

4.1 Timing analysis of each phase of the landing motion

In this study, jump height was not significantly different between participants who jumped with and without verbal instructions. In general, when objects fall from the same height, their velocities are approximately equal. Maximum vertical fall velocity did not differ significantly in this study. Therefore, the momentum at initial landing was also not significantly different during jumping with or without verbal instructions. In this study, the momentum at the terminal landing time was estimated to be zero. Therefore, the change in momentum during the landing phase was almost the same with and without verbal instructions.

Vertical ground reaction forces with verbal instructions were lower than those without, in line with previous studies[14)-19)]. Because the change in momentum during landing was not significantly different with and without verbal instructions, we considered the duration of each phase of landing (Figure 2 as Motion capture stick pictures in a trial. ③ : Initial landing, ④ : The maximum vertical reaction force time in landing, and ⑤ : The terminal landing) would be different with and without verbal instructions, in accordance with the linear momentum–impulse theorem[20)]. In this study, we compared the kinematic characteristics with and without verbal instructions.

The falling phase commenced after reaching the highest jumping point. A comparison of the duration from the highest jumping point to the leg flexion start time, with and without verbal instructions, showed that the former was shorter. All participants started leg bending in space before landing when performing jump-landing tasks with verbal instructions. Some participants did not bend their legs before landing, while performing the jump-landing task without verbal instructions. The inclusion of verbal instructions resulted in an extended landing preparation time and more pronounced leg bending in space, before landing. In addition, the duration of the ground collision during landing (Δt) and the landing phase (L_t) among participants with and without verbal instructions was longer in the former. During landing, the leg flexion range with verbal instructions was significantly greater than that without verbal instructions. These changes are expected to enhance the shock absorption.

Air resistance may be the reason why the falling speed, calculated from the trajectory of the reflective marker, is lower than the theoretical falling speed calculated from the law of conservation of energy. From the correlation between the two calculations, we can more accurately estimate the falling speed immediately before landing, using the jump height. Consequently, even on a field without a force plate system, the average value of the vertical ground reaction force, applied upon landing, can be roughly estimated from the jump height, body weight, and landing phase time.

4.2 Comparison of joint angular range, joint angular velocity, and joint angular acceleration during landing in the lower extremities during landing

The difference in the ratio of right leg length decreases with and without instructions was due to the difference in the range of motion of the hip and knee joints. There was no difference in the range of motion of the ankle joints with or without instructions. Likewise, there was no difference in maximum angular velocity between the hip and knee joints with and without instructions. The difference in landing time with and without instructions was thought to be due to the difference in the maximum angular velocity of the ankle joint movement. There was no difference in angular velocity between the hip and knee joints with or without instructions. The increase in the range of motion of the hip and knee joints due to the instructions was thought to be caused by an earlier start of flexion and an extension of the bending time, due to an extension of the landing time. When instructions were provided, the maximum angular acceleration of the knee joint movement, in the extension direction, and the ankle joint movement, when the landing motion was completed, were smaller than when instructions were not provided. With instructions, the impact on the knee and ankle joints upon completion of the landing motion is alleviated. The adduction and abduction movements of the hip joint during landing vary significantly among individuals, and a thorough study is not possible.

5. Conclusion

When participants jumped while receiving verbal instructions on landing impact absorption, their legs started bending earlier to absorb the impact; moreover, the landing phase and duration of collision during ground landing were longer. The difference in landing time with and without instructions was thought to be due to the difference in the maximum angular velocity of the ankle joint movement. The duration of the ground collision during the landing and the landing phases were similar.

6. Acknowledgements

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7. Funding

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Appendix

p; momentum

$F = dp/dt$ — F; *Force*

$dp = F(t)dt$ — t_i ; *a time just before the collision*

t_f : *a time just after the collision*

$$\int_{t_i}^{t_f} dp = \int_{t_i}^{t_f} F(t)dt$$

The left side of this equation gives us the change in momentum: $p_f - p_i = \Delta p$.

The right side, which is a measure of both the magnitude and duration of the collision force, is called the impulse J of the collision, $\boldsymbol{J} = \int_{t_i}^{t_f} \boldsymbol{F}(t)dt$ (impulse defined).

Thus, the change in an object's momentum is equal to the impulse on the object: $\Delta p = J$ (linear momentum – impulse theory).

In many situations, we do not know how the force varies with time, but we do know the average of magnitude F_{ave} of the force and the duration Δt (= $t_f - t_i$) of the collision. Thus we can write the magnitude of the impulse as $J = F_{ave} \Delta t$[20].

References

1) Dufek JS, Bates BT, 1991, Biomechanical factors associated with injury during landing in jump sports. Sports Med, 12: 326 – 337.
2) Johnson K, 2003, Tears of cruciate ligaments of the knee: US Armed Forces: 1990 – 2002. Med Surveill Mon Rep, 9: 2–6.

3) Kirkendall DT, Garrett WE Jr, 2000, The anterior cruciate ligament enigma: Injury mechanisms and prevention. Clin Orthop Relat Res, (372): 64 – 68.
4) Baus J, Harry JR, Yang J, 2020, Jump and landing biomechanical variables and methods: A literature review. Crit Rev Biomed Eng, 48: 211 – 222.
5) McNair PJ, Marshall RN, 1994, Landing characteristics in subjects with normal and anterior cruciate ligament deficient knee joints. Arch Phys Med Rehabil, 75: 584 – 589.
6) Hewett TE, Ford KR, Hoogenboom BJ, Myer GD, 2010, Understanding and preventing ACL injuries: Current biomechanical and epidemiologic considerations—Update. N Am J Sports Phys Ther, 5: 234 – 251.
7) Myer GD, Ford KR, Hewett TE, 2004, Methodological approaches and rationale for training to prevent anterior cruciate ligament injuries in female athletes. Scand J Med Sci Sports, 14: 275 – 285.
8) Turner CH, Robling AG, 2005, Exercises for improving bone strength. Br J Sports Med, 39: 188 – 189.
9) Cronin JB, Bressel E, Finn L, 2008, Augmented feedback reduces ground reaction forces in the landing phase of the volleyball spike jump. J Sport Rehabil, 17: 148 – 159.
10) McClay IR, Robinson JR, Andriacchi TP, Frederick EC, Gross T, Martin P, Valiant G, Williams KR, Cavanagh PR, 1994, A profile of ground reaction forces in professional basketball. J Appl Biomech, 10: 222 – 236.
11) Otago L, 2004, Kinetic analysis of landings in netball: Is a footwork rule change required to decrease ACL injuries? J Sci Med Sport, 7: 85 – 95.
12) Stacoff A, Kaelin X, Stuessi E, 1988, The impact in landing after a volleyball block. In: deGroot G, Hollander AP, Huijing PA, van Ingen Schenau G, eds. Biomechanics XI-B. Amsterdam: Free University Press, 694 – 700.
13) Aerts I, Cumps E, Verhagen E, Verschueren J, Meeusen R, 2013, A systematic review of different jump-landing variables in relation to injuries. J Sports Med Phys Fitness, 53: 509 - 519.
14) Prapavessis H, McNair PJ, 1999, Effects of instruction in jumping technique and experience jumping on ground reaction forces. J Orthop Sports Phys Ther, 29: 352 - 356.
15) Oñate JA, Guskiewicz KM, Sullivan RJ, 2001, Augmented feedback reduces jump landing forces. J. Orthop Sports Physiol Ther, 31: 470 - 538.
16) McNair PJ, Prapavessis H, Callender K, 2000, Decreasing landing forces: Effect of instruction. Br J Sports Med, 34: 293 - 296.
17) Oñate JA, Guskiewicz KM, Marshall SW, Giuliani C, Yu B, Garrett WE, 2005, Instruction of jump-landing technique using videotape feedback: altering lower extremity motion patterns. Am J Sports Med, 33: 831 - 842.
18) Ericksen HM, Gribble PA, Pfile KR, Pietrosimone BG, 2013, Different modes of feedback and peak vertical ground reaction force during jump landing: A systematic review. J Athl Train, 48: 685 - 695.
19) Ericksen HM, Thomas AC, Gribble PA, Armstrong C, Rice M, Pietrosimone B, 2016, Jump–landing biomechanics following a 4-week real-time feedback intervention and retention. Clin Biomech (Bristol Avon), 32: 85 – 91.
20) Walker J, Halliday D, Resnick R, 2013, Chapter 9, Center of Mass and Momentum, Walker J, Halliday D, Resnick R, Fundamentals of physics 10th edition. Wiley, New York, 226 - 227.