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Investigation of the Relationship between Vertical Stiffness and Time to Stability Index during Landing

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Original Article

Abstract

Introduction: Theoretically, stiffness is effective in the stability and can subsequently reduce the risk of injury. The aim of this study was to investigate the relationship between vertical stiffness and time to reach stability during landing.

Materials and Methods: Twenty healthy active men participated voluntarily in this study. Vertical hopping tests were performed bilaterally, unilaterally on dominant leg, and unilaterally on non-dominant leg with self-selected, controlled (frequency: 2.2 Hz), and maximal strategies during which vertical stiffness variables were determined . Single-leg landing test from platform was performed to determine the variables of time to reach stability in vertical, anterior-posterior (AP), and medio-lateral (ML) directions on the force plate. The relationship between vertical stiffness and time to reach stability variables was determined by Pearson correlation test ($P \leq 0.05$).

Results: A significant positive relationship was observed between maximum unilateral vertical stiffness on dominant leg ($r = 0.45$, $P = 0.048$) and non-dominant leg ($r = 0.52$, $P = 0.012$) with time to reach stability in AP direction.

Conclusion: These findings suggest that high level of vertical stiffness increases the AP time to reach stability and consequently increases the risk of associated injuries.

Keywords: Vertical stiffness; Hopping; Time to stability; Landing

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Introduction

In recent years, research on lower limb stiffness has had an increasing trend; because researchers are trying to better understand the complexities of lower limb mechanics. Vertical stiffness describes the relationship between the amount of lower limb flexion and the external force applied (1-3). Hopping is a simple, relatively controlled movement task with spring-like features suitable for calculating vertical stiffness (4) and is often used in studies conducted to determine vertical stiffness. This task can be performed bilaterally and unilaterally, as well as with different strategies or constraints in terms of height and frequency (self-selected, controlled, and maximal) of jump (5). How to perform hopping has a direct effect on the stiffness values (1,3).

The results of various studies have shown that stiffness is correlated with performance and risk of injury (1,6-9). High and low levels of stiffness are associated with an increased risk of hyperactivity injuries and soft tissue injuries (STI), respectively (1). However, so far there have been limited studies on the association of stiffness with the risk of injury. Negative correlation between hamstring stiffness and anterior tibial transfer rate and lack of significant relationship between hamstring stiffness and landing kinematics (knee flexion and valgus) are among the results of studies (10). Watsford et al. (6) and Pruyn et al. (11) conducted two prospective studies and concluded that excessive lower limb stiffness and asymmetric stiffness of left and right legs were associated with STI in football during the season. Additionally, another set of evidence has associated high stiffness with some risk factors for injury (12-

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14) and some studies have associated low stiffness with some other risk factors for injury (1,13).

Due to the lack of studies on the relationship between stiffness and risk factors for injury and also the contradictory results reported, according to researchers, expressing accurate opinions about this relationship requires further studies in this area (15). In this regard, the relationship between stiffness and balance and stability, which in addition to helping to improve performance, is also a risk factor for injury, has not been studied. However, theoretically, one of the important functions of stiffness is its potential role in providing stability that can reduce the risk of injury (16). The time to stability (TTS) variable specifies the time required to return to the stable state after landing (17). These three variables have been examined many times and are considered as risk factors for the lower extremities. Therefore, it is important to discover the relationship between stiffness and the TTS index in three directions. Moreover, due to the trainability of stiffness, the results of the present study can help trainers to provide specialized exercises aimed at decreasing or increasing stiffness to improve performance and reduce the risk of injuries associated with balance and stability. So far, no study has examined the relationship between stiffness and these three variables. Therefore, this study is conducted with the aim to determine the relationship between vertical stiffness and the TTS variable in the three vertical, anterior-posterior (AP), and medio-lateral directions.

Materials and Methods

This was a quasi-experimental, correlational study with the statistical population consisting of male students active in the field of physical education (PE) and sports sciences at Kharazmi University, Tehran, Iran. From among the statistical population, 20 individuals were selected for the study by the convenience sampling method as a statistical sample. The minimum number of samples was estimated 18 using G*Power software and based on the Pearson's correlation coefficient test with power of 0.8, effect size of 0.35, and alpha correlation of 0.05.

The objective and procedure of the test were explained to the subjects. They then completed the consent and demographic characteristic forms. The inclusion criteria included having at least two sessions per week and at least one hour of exercise per session. Having any abnormalities or injuries in the lower extremities during the last six months were also considered as the exclusion criteria. Observance of ethical principles in the tests in the study was reviewed in the ethics committee of the Institute of Physical Education and Sports Sciences and was approved with the code IR.SSRI.REC.1396.126.

The ground reaction force (GRF) information was recorded using a Kistler force plate (9281, Switzerland) at a sampling frequency of 1000 Hz. The leg with which the subject hit the ball was determined as the dominant leg. Prior to the tests, the subjects were asked to perform hopping and single-leg landing tests after five minutes of warm-up, which included running, stretching, and jumping.

The subjects performed the hopping test with three strategies (self-selected, controlled, and maximal) and bilaterally, unilaterally on the dominant leg, and unilaterally on the non-dominant leg. In each hopping test, the subjects were asked to perform 15 consecutive hops barefoot on the force plate with arms akimbo. Before recording the data, the subjects were taught how to perform the tests and were allowed to practice the task (about 4 to 5 minutes) until they felt comfortable with the task. In the self-selected strategy, the subject was asked to perform the hopping with the desired frequency and height. In the controlled strategy, using a digital metronome to adjust the frequency, the subject performed hopping at a frequency of 2.2 Hz (2.2 hops per second) (18,19). In the maximal strategy, the subject performed hopping with the aim of reaching the highest possible height and with the shortest time of contact with the ground (2).

After performing the hopping tests, the subject was taught how to perform the landing test from the platform. A platform with a height of 35 cm was placed at a distance of 10 cm from the force plate. The subject was asked to stand on the platform with his arms akimbo, barefoot, and on the non-dominant leg, and by jumping on the dominant leg, land in the center of the force plate and as soon as he landed, he was asked to straighten his body and look forward for about 20 seconds and maintain his balance in the same position. Sliding of the landing foot on the force plate, contact of the other foot with the ground, or using handles to maintain balance were the three criteria for incorrect execution of the task (20). Two correct landings were considered for each subject. When landing and maintaining balance, the force plate recorded the GRFs.

From all the data recorded using the force plate during the hopping test, data related to five intermediate hops (sixth to tenth hops), including a contact phase and a flying phase, were separated for further analysis (2,21). A fourth-order Butterworth low-pass filter (LPF) with 50 Hz cut-off frequencies was used to filter the force plate data (vertical component of the GRF) (2,21). The vertical stiffness was obtained by dividing the maximum

GRF (F_{max}) by the vertical displacement value of the center of mass (ΔY) during the ground contact phase (Equation 1) (22).

Equation 1 $$k\_ver = F\_max / \Delta Y$$

F_{max} was extracted directly from the force plate data. The changes in the displacement of the center of mass in the vertical direction were estimated double-integrating the vertical GRF (23) and the change in height of the center of mass (ΔY) during the eccentric phase of the hopping contact phase was calculated. Finally, the stiffness obtained for five hops was averaged.

To calculate the TTS, using the data recorded by the force plate, the force signals were first normalized by dividing by the subject's body weight and then filtered by a second-order Butterworth two-way LPF with a cut-off frequency of 12 Hz. The average force signal over a five-second period of 7 to 12 seconds was calculated and considered as the baseline of stability. After the force signals were rectified with their absolute magnitude, the standard deviation (SD) of the signal was calculated from 7 to 12 seconds. Then, from the moment of reaching the peak to 12 seconds after landing, a third-degree polynomial function was fitted to the force data. The moment when the distance between this third-degree curve and the baseline was less than a certain amount was considered as the moment of reaching stability. This specific value was set for vertical, AP, and medioltral signals respectively equal to 30, 15, and 7 times the SD set for the same signal (within 7 to 12 seconds) (24).

The above-mentioned process was coded in MATLAB software (R2018a, Math Works Ink, USA) and was performed in order to calculate the study variables. Data were described using mean and SD and the normality of data distribution was assessed using the Shapiro-Wilk test. To determine the relationship between the study variables, the Pearson's correlation coefficient test was used at the significance level of 0.05.

Results

The mean and SD of the demographic characteristics of the subjects are presented in table 1.

A description of the vertical stiffness data is provided in table 2. The bilateral vertical stiffness related to controlled strategy was about 34% ($P = 0.001$) and 62% ($P < 0.001$), respectively, greater than the bilateral vertical stiffness related to the self-selected and maximal strategies. In addition, the unilateral vertical hopping stiffness values were smaller than those of the bilateral hopping in the controlled (14%), self-selected (24%), and maximal (10%) strategies. The mean values of the TTS variable in the single-leg landing in the three vertical, AP, and medio-lateral directions were 1.14 ± 0.51, 1.42 ± 0.39, and 1.38 ± 0.86, respectively.

Table 1. Demographic characteristics of the subjects

Variable	Mean ± SD
Age (year)	24.58 ± 1.64
Weight (kg)	60.16 ± 4.74
Height (m)	1.76 ± 0.06
BMI (kg/m^2)	19.37 ± 1.38

BMI: Body mass index

The results of the correlation test in the vertical stiffness variable by strategy and execution method with the TTS variable in the three medio-lateral, AP, and vertical directions are shown in table 3. Given the results, among the vertical stiffness values calculated with different strategies and methods of implementation, only the relationship between maximum unilateral lower extremity stiffness on the dominant leg and on the non-dominant leg with the TTS variable in the AP direction was positive and significant.

Discussion

The purpose of this study was to investigate the relationship between the vertical stiffness variable in hopping and the TTS variable in three directions in landing. The findings indicated that among the variables measured, only the unilateral maximum vertical stiffness (on the dominant leg and on the non-dominant leg) had a significantly positive relationship with the TTS in the AP direction; While there was no significant relationship between the bilateral vertical stiffness as well as the self-selected and controlled vertical stiffness with the TTS in any of the three directions.

Fransz et al. used a similar method to calculate the TTS index and reported the value of this variable in the medio-lateral, AP, and vertical directions, respectively, about 1, 1.2, and 0.8 (24), which is consistent with the present study in terms of the TTS values.

Table 2. Mean vertical stiffness during hopping tests by strategy and method of execution (N/m.km)

Strategy	Bilateral	Unilateral on the dominant leg	Unilateral on the non-dominant leg
Self-selected	166.86 ± 53.95	145.58 ±37.57	154.50 ± 29.72
Controlled	224.45 ± 54.34	180.79 ± 47.57	183.54 ± 40.31
Maximal	138.22 ± 65.04	134.69 ± 44.43	138.22 ± 30.90

Data are reported as mean ± standard deviation (SD).

Table 3. Results of the correlation test between vertical stiffness (N/m.km) and time to stability (TTS) in three directions (seconds)

Variable	Statistics	TTS in vertical direction	TTS in AP direction	TTS in medio-lateral direction
Self-selected bilateral stiffness	r	0.13-	0.16	0.03-
	P	0.360	0.250	0.840
Self-selected dominant leg stiffness	r	0.11	0.22	0.14-
	P	0.540	0.230	0.500
Controlled bilateral stiffness	r	0.04-	0.11	0.10
	P	0.840	0.420	0.580
Controlled dominant leg stiffness	r	0.15-	0.10-	0.19-
	P	0.470	0.570	0.330
Controlled non-dominant leg stiffness	r	0.05-	0.18	0.28
	P	0.770	0.260	0.140
Maximal bilateral stiffness	r	0.14	0.36	0.27
	P	0.290	0.060	0.130
Maximal dominant leg stiffness	r	0.06	0.52*	0.34
	P	0.750	0.012	0.058
Maximal non-dominant leg stiffness	r	0.10	0.45*	0.31
	P	0.540	0.018	0.060

TTS: Time to stability; AP: Anterior-posterior
*Significant at the level of P < 0.050

Slightly higher values of TTS in the present study than in the study of Fransz et al. seems reasonable considering the fact that the landing height was 30 cm in the present study and 20 cm in the study of Fransz et al. (24).

So far, no study has examined the relationship between vertical stiffness and the TTS, and only the possible role of stiffness in ensuring system stability and reducing the risk of injury through this has been mentioned (16). In many sports activities, it is important to maintain balance and achieve stability after landing in terms of functionality as well as in order to prevent injury. For example, after a spike in volleyball or a head in football, landing with a balanced posture allows the player to prepare faster to continue the game and perform better, or in sports such as gymnastics, part of the athlete's score is calculated based on his/her ability to achieve stability and balance during landing. Moreover, it has been stated that the long TTS in three directions is a sign of a defect in the neuromuscular control system (17) and has been introduced as a risk factor for lower limb injuries (17,25). Therefore, longer TTSs after landing can lead to a decreased performance and increased risk of injury in athletes. The results of the present study suggest that vertical stiffness is directly related to the TTS in the AP direction. Therefore, a higher vertical stiffness can lead to poor performance and an increased risk of injury in athletes. Furthermore, the fact that the AP stability of the knee joint is one of the most important factors in preventing anterior cruciate ligament (ACL) injury (26,27) increases the risk of excessive vertical stiffness. Researchers have also linked low stiffness to STI; Because low stiffness is associated with further flexion of the lower limb joints, and although it reduces the shock due to impact by absorbing energy during landing, it places the limb at the end of the range of motion (ROM) and leads to stress on ligaments and the risk of STI. Therefore, it seems that too much or too little stiffness cannot be an advantage in reducing the risk of injury, and there may be an optimal amount for it.

The lack of a significant relationship between vertical stiffness and TTS in the vertical and medio-lateral directions, can be related to the vertical stiffness calculation method. Vertical stiffness is calculated by dividing the maximum force by the vertical changes of the center of mass in the hopping eccentric phase (8).

The vertical changes of the center of mass were also a function of the amount of the lower limb flexion, which occurs in the AP direction and is controlled by flexors and extensors (1). Certainly, AP stability is more dependent on the function of flexors and extensors. The above argument can be the probable reason for the lack of a significant relationship between vertical stiffness and the TTS in the vertical and medio-lateral direction and a significant relationship between vertical stiffness and the TTS in the AP direction.

Limitations

One of the limitations of the present study was the sample group that were non-trained athletes. Therefore, the generalizations of the findings to the athlete group should be made with caution and requires further investigation. Another case was related to the limitation of using the motion analysis system to calculate the vertical displacement of the center of mass. In the present study, to determine the vertical stiffness and vertical displacement of the body mass center, the method of double-integrating the vertical GRF was used.

Recommendations

It is recommended that a similar study be performed on a group of trained athletes in order to generalize the results to the group of athletes with more confidence. In order to eliminate the error caused by calculating the changes in the center of mass using the method of double integration of the force plate data, it is suggested to use multi-segment analysis using the motion analysis system instead.

Conclusion

The results of the present study showed that excessive vertical stiffness increases the TTS in the AP direction; while it is not correlated with the TTS in the vertical and medio-lateral directions.

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Authors' Contribution

Mohammad Amin Mohammadian: study design and ideation, study support, executive, and scientific services, providing study equipment and samples, data collection, analysis and interpretation of results, specialized statistics services, manuscript preparation, specialized evaluation of manuscripts in terms of scientific concepts, final manuscript approval to be submitted to the journal office, responsibility for maintaining the integrity of the study process from the beginning to the publication, and responding to referees' comments; Heydar Sadeghi: study design and ideation, study support, executive, and scientific services, analysis and interpretation of results, specialized statistics services, manuscript preparation, specialized evaluation of manuscripts in terms of scientific concepts, final manuscript approval to be submitted to the journal office, responsibility for maintaining the integrity of the study process from the beginning to the publication, and responding to referees' comments; Mehdi Khaleghi-Tazji: study design and ideation, study support, executive, and scientific services, specialized evaluation of manuscripts in terms of scientific concepts, final manuscript approval to be submitted to the journal office, responsibility for maintaining the integrity of the study process from the beginning to the publication, and responding to referees' comments.

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Conflict of Interest

The authors declare no conflict of interest.

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