Reproducibility of Dynamic Body Balance Measurement by Center of Foot Pressure Analysis Immediately after Single-Leg Hop Landing

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Summary: Dynamic balance was evaluated using the trajectory length of the center of foot pressure (COP) in the early phase from immediately after landing to the time of pastoral maintenance. Ten young volunteers with an average age of 23.8 years were asked to stand on one foot on a horizontal floor, hop forward half a step and land on one foot 10 times on each of 3 non-consecutive days. The peak of the vertical component of the floor reaction force (Fz), and the initiation time of the maximum value (tz) and COP trajectory length were measured by a force plate (AMTI, Ltd.). None of the subjects complained of any feeling of fear or loss of balance during the 3 days. The interclass correlation coefficient values of Fz and tz over the three days were 0.75 or higher. Single-leg hop for half a step as a motor task enabled safe measurement of COP trajectory length with high reproducibility. Fz reached its peak within 200 ms after landing and the COP trajectory length within 200 ms after landing accounted for approximately 50% of the total COP trajectory length at one second. Although the length differed in each subject, the interclass correlation coefficients for COP up to 100 ms and 200 ms were 0.68 and 0.80, respectively. The COP trajectory length within 200 ms after landing was considered to be useful as an objective criteria for the evaluation of dynamic balance in the early phase after landing.

Key words dynamic balance, single-leg hop, center of pressure, force plate, interclass correlation coefficient

INTRODUCTION

Balance is described as the ability to maintain equilibrium in a gravitational field by keeping or returning the center of body mass over its base of support [1]. Postural stability is a more specific description of human balance. Postural stability can be defined as the ability of an individual to maintain their center of gravity (COG) within the base of support (BOS). Postural stability can be further identified as “static” or “dynamic” postural stability. An example of static postural stability is standing quietly without moving, while dynamic postural stability refers to the ability to maintain posture while performing specific movements, such as reaching forward or walking.

To date, various methods have been reported in the evaluation of balance, including stabilometry [2] and functional reach test (FRT) [3] as representative methods for static balance evaluation, and Timed Up and Go (TUG) [4] and Berg Balance Scale (BBS) [5] as dynamic methods for balance evaluation. Evaluation and improvement of balance are important in the training of athletes and rehabilitation of patients with injuries received during sports activities. However, in the evaluation of balance during movement, dynamic movement, that is, jumping/landing and rapid slowdown, should be examined instead of static movement [6]. In particular, it has been clarified that anterior cruciate ligament...
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Ciate ligament (ACL) injury during sports activities tends to occur in the early phase after landing [7,8]. Therefore, it would be important to measure dynamic balance ability in the early phase immediately after landing. However, there have been no reports on its quantitative evaluation. Furthermore, while the motor task used to measure dynamic balance is important, the measurement should be performed safely without engendering any feeling of fear. While the vertical drop jump and single-leg hop are often performed in clinical evaluation after ACL reconstruction surgery [9,10], this method affords a high risk for patients with no sports experience and those in the early phase after surgery on the knee joint. Thus, it would be useful to identify a motor task that can be safely performed by a wider range of subjects.

This study was performed to: 1) examine whether single-leg hop/landing with comparatively low load could be performed safely as a motor task, and 2) evaluate dynamic balance by measuring the trajectory length of the center of pressure (COP) in the early phase from immediately after landing to the time of postural maintenance, using a device to measure the floor reaction force that has been widely used as an evaluation marker of static balance ability. The objective was to establish a safe and effective method of measuring dynamic balance in the early phase after landing.

METHODS

Participants

The subjects were 10 young non-athlete volunteers who had no history of injury in the lower extremities (male: 1, female: 9) (average age: 23.8±4.7 years old, average height: 159.9±10.0 cm, average weight: 51.0±7.2 kg and average foot size: 22.8±2.0 cm). This study was performed in accordance with the Declaration of Helsinki and after obtaining the approval from the ethics committee of the School of Comprehensive Rehabilitation, Osaka Prefecture University. We explained the objectives and importance of this study to the subjects, and obtained oral and written informed consent from them before the experiments.

Measurement

The motor task was a single-leg hop, in which the subject was asked to stand on one foot on a horizontal floor, hop forward and land on the same foot (Fig. 1). The length of hop was determined to be a half of one step, which was measured when a subject walked 10 m on flat ground. The subjects were asked to cross their arms on their chest and stop after landing, maintaining the flexed position of the lower extremities.

The measurements of the floor reaction force were made using a Force Plate (AMTI, Ltd.), and analysis software (Technology Service) was used to record the measurement data and calculate the COP trajectory length. Based on the data of the measured floor reaction force, movement distance of the COP during the first second immediately after landing was calculated to determine the total COP trajectory length. We then calculated the ratio of total COP trajectory length for every 100 ms interval, COP trajectory length up to 100 ms and 200 ms, the peak of the vertical component of the floor reaction force (Fz), and the initiation time of the maximum value (tz). The COP trajectory length and floor reaction force were normalized based on the leg length and weight, respectively, to calculate.
the average of 10 measurements for each measurement item. The COP trajectory length up to 20 ms was excluded because the exact COP could not be calculated due to the extremely small Fz values immediately after landing. Further, we statistically assessed the reproducibility of each measurement value obtained on 3 non-consecutive days, using the interclass correlation coefficient (ICC (1.1)), and examined the dispersion of these values in each subject.

RESULTS

Among the subjects, no one complained of any feeling of fear or loss of balance during the 3 days, and thus the measurements were considered to have been performed safely.

1. Total COP trajectory length during 1 second

The average total COP trajectory length up to 1 second during the 3 days in each subject is shown (Fig. 2). The interclass correlation coefficient was 0.79 (Table 1).

2. The ratio for the total COP trajectory length for each 100 ms interval.

<table>
<thead>
<tr>
<th>Table 1. Interclass correlation coefficient for each value</th>
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<td>1sec COP</td>
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![Fig. 2. Average total COP trajectory length up to 1 second during the 3 days in each subject.](image)

![Fig. 3. Ratio for the total COP trajectory length up to 1 second after landing in each measurement day.](image)
The ratio for the total COP trajectory length up to 1 sec after landing on each measurement day is shown (Fig. 3). The ratio of the total length on each measurement day was 28 ± 7%, 31 ± 9%, and 31 ± 8% for the first 20-100 ms on the 1st, 2nd and 3rd day, respectively, while that from 100-200 ms was 19 ± 5%, 19.6 ± 5%, and 19 ± 6% on the 1st, 2nd and 3rd day, respectively. However, the ratio for every 100 ms interval after 200 ms was 10% or lower on each of the 3 days.

3. COP trajectory length up to 100 ms and 200 ms

The COP trajectory lengths up to 100 and 200 ms on each of the 3 days are shown for each subject (Table 2). Although the length differed depending on the subject, the interclass correlation coefficients for COP up to 100 ms and 200 ms were 0.68 and 0.80, respectively (Table 1).

4. Fz, tz

The average Fz and tz values over the 3 days for each subject are shown (Table 3). The interclass correlation coefficients for Fz and tz were 0.93 and 0.78, respectively (Table 1).

**DISCUSSION**

**Motor task for measurement of dynamic balance**

Since the subjects undergoing assessment of dynamic balance are often elderly, athletes, or postoperative patients, safety is essential for such measurements. Although several motor tasks are used in the functional evaluation after surgery of the knee joint, a vertical-drop jump from a height of 20-30 cm and single-leg hop to measure the maximum distance of hop are used to assess the risk of fall [9-11]. In addition, in one study of the hop test, in which a strain gauge was implanted in ACL of a living body, the ACL tension was maximized when the floor reaction force was at...
its highest [12]. Thus, stress upon landing should be minimal from the perspective of injury prevention. Since the force exerted at single-leg hop landing in this study was approximately twice the weight of both legs, the experiments could be performed safely with no fear in all subjects. Regarding the reproducibility of Fz and tz over the 3 days, the ICC values were 0.75 or higher. Since it has generally been reported that the reproducibility can be considered high when the interclass correlation coefficient is 0.7 or higher, it was shown that single-leg hop landing was reproducible. In addition, although the differences in the COP trajectory length up to 200 ms after landing and tz were small between measurement days, the differences between subjects were large. These differences were considered to be indicative of differences in their dynamic balance ability.

2. The results of early-phase balance evaluation

In recent years, studies of the mechanisms underlying initial ACL injury using images of injuries have suggested that injury could occur within 100 ms after landing of the foot, that is, immediately after landing [9,10]. It is also known that the reaction time of the quadriceps to a visual signal would be approx. 180 ms [13]. In this study, the peak Fz was observed from 33 to 162 ms after landing, and the measurement values obtained within 200 ms after landing accounted for about 50% of the total COP trajectory length up to 1 second. Therefore, based on the above results, it was suggested that evaluation of balance ability within 200 ms would be important.

Thus, when we subsequently examined the reproducibility of the COP trajectory length, the interclass correlation coefficient of COP for 100 ms was 0.68, while that of COP up to 200 ms was 0.80, suggesting that the reproducibility of COP trajectory length in 200 ms would be high. By analyzing the COP trajectory length 200 ms after landing using the single-leg hop movement, dynamic balance ability could be evaluated in the early phase after landing, with reproducible results.

The limitations of this study include the small number of subjects (10) and the fact that the subjects were limited to healthy volunteers in their 20s-30s. Since balance functions can deteriorate in the elderly, those who don’t engage in sports, and patients in the early postoperative phase after surgery of the knee joint, further studies should be conducted with more subjects to increase the reliability of these findings. Furthermore, this measurement method needs to be verified by comparing its results with those of established dynamic balance tests such as the functional reach test and star excursion balance test. In addition, in the current study, we assessed the COP to indicate the point of action of floor reaction force, which is different from the center of gravity (COG). Measurement of the COG is not easy because it requires complex equipment, and movement of the COG could be affected by the floor reaction force. Thus, in this study, we used COP trajectory length because it could be measured easily.

However, since single-leg hop for half a step as a motor task enabled safe measurement of COP trajectory length with high reproducibility, we considered it to be useful as an objective method for the evaluation of dynamic balance in the early phase after landing. In the future, comparisons of hopping in different directions, laterality and other movements should be performed to investigate how dynamic balance is affected by various motor tasks, while patients with poor balance capacity could be examined by this current measurement method.

CONCLUSION

Based on the facts that Fz reached its peak within 200 ms after landing from a single-leg hop and accounted for approximately 50% of the COP trajectory length at 1 second after landing, and that the results were reproducible, it was suggested that the analysis of COP trajectory length within 200 ms after landing would be useful for the evaluation of dynamic balance in the early phase. The present study also found that the single-leg hop for half a step was a safe and effective motor task for measurement of COP trajectory length.

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