INTRODUCTION

Improvements in muscle strength, flexibility, and balance are required to facilitate recovery from or prevent sports injuries. Thus, it is critical to be able to evaluate those attributes objectively. Objective criteria for evaluating muscle strength and flexibility are well established, and are used to determine the effectiveness of an athlete’s training or rehabilitation while recovering from a sports injury. Postural stability can be classified as being “static” or “dynamic” [1,2]. To date, several methods have been used to evaluate balance, including stabilometry [3] and functional reach test (FRT) [4] as methods for static balance evaluation, and Timed Up & Go (TUG) [5] and Berg Balance Scale (BBS) [6] as methods for dynamic balance evaluation. However, measurements using previous methods of dynamic balance evaluation do not directly reflect motion characteristics, time, or distance of the center of gravity, and motor tasks do not typically include highly dynamic motions like those used in sports.

Balance refers to the adjustment of position in active movements and the maintenance of an appropriate position in response to external stimuli. Maintenance
of balance requires normal pressure and an appropriate integration process at the higher center with continuity of the center of gravity (COG) within the support plane. The mode of postural control during that action can be measured as changes occur in ground reaction force (GRF) and center of pressure (COP). Thus, we developed a method for dynamic balance evaluation that focuses on GRF and COP during a single-legged forward hop landing. This motion mimics COG movement and abrupt acceleration and deceleration used in sports. We also found that the length of COP trajectory traveled up to 200 ms after landing is a quantitative and highly reproducible index for assessing dynamic balancing ability [7].

Motion in sports is not limited to motion in the forward direction. Lateral cutting maneuvers and changes in direction are key techniques used in ball sports to elude an opponent. However, those maneuvers are considered more likely to result in lower extremity injury since the lower extremities are subjected to an excessive GRF [8]. In addition, elderly individuals fall in the lateral direction, and a large proportion of such falls results in fracture of the femoral neck [9,10]. A better understanding of whether balance characteristics during lateral disruption of the body’s balance differ from balance characteristics during forward motion is required in order to prevent lower extremity injuries during sports and falls among the elderly. Accordingly, one aim of this study was to assess whether COP trajectory length and peak GRF values after a single-leg hop landing differed when hopping forward versus laterally. Another aim of this study was to ascertain disparities in balance characteristics due to differences in hop direction. COP trajectory length reflects the extent of postural sway after landing, and peak GRF values reflect the force of impact upon landing. COP trajectory length and peak GRF values were hypothesized to be higher when hopping laterally relative to when hopping forward.

METHODS

The subjects were 24 young non-athlete volunteers who had no history of injury in the lower extremities (male: 9, female: 15) (average age: 22.1±3.2 years old, average height: 163.7±8.0 cm, average weight: 54.4±7.4 kg and average foot size: 23.9±1.9 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 experiments.

The motor task performed by participants of this study was a single-leg hop, which required standing on one leg, hopping on the same leg, landing on that leg, and then maintaining a static standing posture. The length of hop was determined to be half of one step, which was measured when a participant walked 10 m on flat ground. Participants were asked to cross their arms on their chest and stop after landing, maintaining the flexed position of the lower extremities. Prior to measurement, participants performed several trials to become accustomed to the action. During measurement, participants hopped in either a forward or lateral direction, ten times in each direction with each leg (Fig. 1).

Software (Technology Service) to assess dynamic balance via a Force Plate (AMTI, Ltd) was used, and GRF data were collected at 1,000 samples per s. We calculated COP as well as COP trajectory length up to 200 ms (200msCOP) and 1 s (1sCOP). COP trajectory length was calculated every 100 ms from landing to 1 s later, and the ratio for COP trajectory length in every 100 ms interval after landing was determined with respect to 1sCOP over time. When COP was calculated, there was a small vertical GRF immediately after landing, precluding accurate calculation of COP, so COP trajectory traveled 20 ms after landing was not analyzed. In order to assess GRF, peak values of frontal, sagittal, and vertical GRF (pF_{ML}, pF_{AP}, and pF_{V}, respectively) were calculated (Fig. 2). 1sCOP and 200 msCOP were normalized to leg length, and peak GRF

![Fig. 1. Measurement method](image-url)

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 subject was asked to cross their arms on their chest and to hop forward (a) and lateral (b). After landing on the same foot, the subject was asked to maintain the flexed position of lower extremities.
values were normalized to body weight. Measured values are expressed as the mean ± standard deviation of ten attempts to hop in a given direction (forward or lateral) and to hop on a given leg (right or left).

For statistical analysis, 2-way analysis of variance for 1sCOP, 200msCOP, and peak GRF ($p_{FML}$, $p_{FAp}$, $p_{FV}$) values was performed with hopping in a given direction and hopping on a given leg as factors. Three-way analysis of variance of COP trajectory length was performed for every 100 ms interval, with hopping in a given direction, hopping on a given leg, and hopping in a given amount of time as factors. For both analyses, a post hoc Tukey’s honest significant test was performed. Statistical analysis of peak GRF values did not detect a main effect of either leg beforehand, so hopping in a given direction and GRF components were chosen. $P < 0.05$ was considered statistically significant.

RESULTS

None of our participants complained of any feeling of fear or loss of balance when landing in either direction, and thus measurements were taken for all ten times the task was performed.

1. The COP trajectory length

The ratio of COP trajectory length up to 1 s after landing is shown (Fig. 3). The distance COP traveled per unit time decreased sharply up until 200 ms after landing. After that point, COP distance traveled per unit time decreased slowly. From 20-100 ms, 200msCOP accounted for 28% of 1sCOP when landing forward on the right leg, 28% when landing forward on the left leg, 33% when landing laterally on the right leg, and 30% when landing laterally on the left leg. From 100-200 ms, 200msCOP accounted for 17% of 1sCOP when landing forward on the right leg, 18% when landing forward on the left leg, 17% when landing laterally on the right leg, and 18% when landing laterally on the left leg. However, the ratio for every 100 ms interval after 200 ms was 10% or lower. Analysis of variance indicated that a main effect was noted only with hopping in a given amount of time. Neither hopping in a given direction nor hopping on a given leg had a significant main effect, and no interaction was noted between the two. The post hoc test indicated that a significantly greater proportion of COP trajectory was traveled in the 20-100-ms and 100-200-ms intervals than in sub-

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**TABLE 1.**

|               | Leg | Forward | Lateral | $p$ - value | Right vs Left |
|---------------|-----|---------|---------|-------------|---------------|
| 1sCOP (% of foot length) | Right | 100 ± 21 | 111 ± 24 | 0.32        | n.s           |
|               | Left | 94 ± 19 | 107 ± 23 | 0.19        |               |
| 200msCOP (% of foot length) | Right | 44 ± 9 | 53 ± 11 | < 0.01      | n.s           |
|               | Left | 41 ± 9 | 50 ± 11 | < 0.01      |               |

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$FML, F_{AP}, F_{V}$ symbols denoting resolved components of ground reaction force.
sequent time intervals. There were no significant differences in COP trajectory traveled after the 200-300-ms interval.

Results for 1sCOP and 200msCOP are shown in Table 1. With the left and right legs, neither hopping in a given direction nor hopping on a given leg had a significant main effect on 1sCOP. In contrast, hopping in a given direction had a significant main effect on 200msCOP. The post hoc test indicated that 200msCOP was significantly greater when hopping laterally than when hopping forward (p < 0.01).

2. The peak value of GRF

Analysis of variance of peak GRF values indicated that hopping on a given leg did not have a significant main effect, so peak GRF values were averaged for the left and right legs, as shown in Fig. 4, to avoid complexity. Hopping in a given direction had a significant main effect on 200msCOP. The post hoc test indicated that 200msCOP was significantly greater when hopping laterally than when hopping forward (p < 0.01). However, significant differences in pF_{AP} when hopping forward or laterally were not observed (p = 0.47).

**DISCUSSION**

The present study aimed to assess whether COP trajectory length and peak GRF values after a single-leg hop landing differed when hopping forward or laterally. Another aim was to ascertain disparities in balance characteristics due to differences in hop direction. 200msCOP reflects postural sway immediately after landing, and we found that 200msCOP was significantly greater when hopping laterally than when hopping forward (Table 1). We also found that hopping in the lateral direction induced greater postural sway than hopping in the forward direction. F_{ML} reflects impact in the frontal direction, and peak GRF values revealed that pF_{ML} was significantly greater when hopping laterally, as expected (Fig. 4). As shown in Fig. 3, the ratio of COP trajectory length in every 100 ms interval with respect to COP trajectory length up to 1 s after landing was significantly greater up until 200 ms after landing than during subsequent time intervals, and this was true for both legs. Moreover, 200msCOP accounted for a similar proportion of 1sCOP when hopping forward or laterally. Consistent with findings from our previous study involving forward hopping [7], the current findings with regard to hopping laterally similarly indicate that assessments focused on 200msCOP are effective.

The multi-directional reach test (MDRT) is a method of measuring balance that takes into account differences in the direction of motion. MDRT is a balance test based on tilting of the trunk in four directions (forward, backward, to the left, and to the right) with a fixed base of support. A previous study concluded that motion in the forward direction is the most stable [13]. The present study found that 200msCOP was significantly smaller when hopping forward than when hopping laterally, indicating that more stable postural control is exhibited after landing. Thus, the current findings are consistent with the study by Tantisuwat et al [13]. Moreover, the current study used a task involving more dynamic movement (i.e., movement of COG and hop landing) to examine the relationship between the direction of motion and balancing ability. In this regard, our results differ from that of Tantisuwat et al. Lateral motion is unstable, regardless of whether the base of support is fixed or whether a hop landing is being performed. This suggests that both forward and lateral balance must be fully taken into account when dealing with problems such as sports injuries and falls by the elderly.

pF_{ML} and pF_{V} are frontal and vertical components, respectively, of GRF. Both pF_{ML} and pF_{V} were significantly greater when hopping laterally than when hopping forward. Both represent the magnitudes of the braking impact applied to the landing leg. The force of impact in these directions is presumably what increased 200msCOP during lateral hopping. The impact of landing is primarily cushioned by flexion of three joints of the lower extremities (ankle, knee, and hip) [14].
When hopping forward, the direction of braking GRF coincides with the direction of joint flexion, so flexion and extension can cushion the force of impact. When hopping laterally, however, the direction of braking GRF acts at approximately 90º to the direction of joint flexion. The ankles and knees lack range of motion in the frontal direction, so braking GRF acting in the frontal direction cannot be adequately cushioned. As a result, pF_{ML} and pF_{V} presumably increase. This is substantiated by the fact that significant differences in pF_{AP} were not noted in the sagittal direction, where the three joints have range of flexion (Fig. 4). In the future, the effects of hopping direction on COP trajectory length and peak GRF values and mechanical joint parameters should be examined. Such work would facilitate a more detailed understanding of mechanisms that cause sports injuries and falls.

The limitations of this study include the fact that participants were limited to healthy volunteers in their 20s-30s. Since balance function can deteriorate in the elderly, those who do not engage in sports, and patients in the early postoperative phase after surgery of the knee joint, further studies should be conducted with more participants in order to increase the reliability of our findings. In addition, the position of the body’s COG is affected by the position of the trunk and upper extremities, so the current study examined only COP trajectory length and peak GRF values. In the future, detailed 3-dimensional motion analysis of the timing of GRF peaks and leg joint moments should be performed.

Despite these limitations, analysis of COP trajectory length up to 200 ms is a useful way to objectively assess dynamic balance immediately after landing, regardless of whether the single-leg hop landing is made in the forward or lateral direction. Our results suggest that COP trajectory length up to 200 ms may have clinical applications (e.g., for assessment of balancing ability of individual athletes) as an index to assess balance training after surgery on a lower extremity, and for early detection of affected balance in a lower extremity, by comparing the left and right lower extremities. In the present study, the hopped distance was half of one step. If this distance were altered, 200msCOP would presumably change as well. In the future, 200msCOP should be measured with different lengths in accordance with the ability of different individuals (e.g., elderly individuals, athletes, or patients who have undergone surgery).

CONCLUSION

200msCOP reflects postural sway immediately after landing, while pF_{ML} and pF_{V} reflect the force of impact upon landing. 200msCOP, pF_{ML}, and pF_{V} were significantly higher when hopping laterally than when hopping forward. When hopping forward or laterally, COP distance up until 200 ms after landing accounted for roughly 50% of the COP distance up until 1 s after landing. Thus, our results suggest that 200msCOP is useful for assessing dynamic balance immediately after hopping laterally or forward and landing.

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