ESTIMATION OF GROUND REACTION FORCES DURING WALKING

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One way to calculate net forces utilizes the Newton-Euler equations where the human body is assumed to consist of solid elements. However, previous research only applied them to open-loop motion in which both legs are off the ground or only one leg is on the ground. It has been problematic to analyse closed-loop motions such as walking in which both feet are on the ground. This study suggested a way to calculate net forces throughout a walking cycle. Furthermore, one walking trial of each subject (3 in total) was conducted to validate with the proposed methods. This study showed that the correlations between force plates and calculated GRF were strong, in particular for the z axis, in the left limb ranged from 0.92 to 0.99, in the right limb from 0.99 to 0.98. Thus, the proposed method was considered to successfully calculate the net forces during walking.

KEY WORDS: ground reaction forces, closed-loop, gait, computer human models.

INTRODUCTION: Previously, computer human models that duplicate the properties and the functions of human have been developed. They are used for the evaluation of product designs, for improvements of working environments, rehabilitation procedures and sport techniques. They can predict net forces accurately and make possible the prediction of movement patterns prior to real-life application. However, it is difficult to analyze a closed-loop motion such as walking in which both feet are on the ground. Previously, net forces were calculated with ground reaction forces of each foot, measured by force plates in the closed-loop motion. But it is not always possible or affordable to have force platforms under each foot. Therefore, this study outlines a method that can calculate net forces of each joint in closed-loop motions without the need for force plates.

METHODS: There are two situations during walking as shown in Figure 1. The first is when only one leg is on the ground. In this case, it is possible to calculate net forces at each joint by proceeding from the distal segments link by link towards the ground leg. The second situation occurs when both legs are on the ground. In this case, the net forces are indeterminate because there is no way to divide the sum of net force from the distal segments into each leg. In this study, net force divided into each leg is assumed to depend on a body gravity position. Then the body gravity position can be calculated from the location of each body elements.
Figure 2 shows the behaviour of the body gravity position when both legs are on the ground (left leg on & right leg off). The distribution of the net force of right leg is 100% and that of left

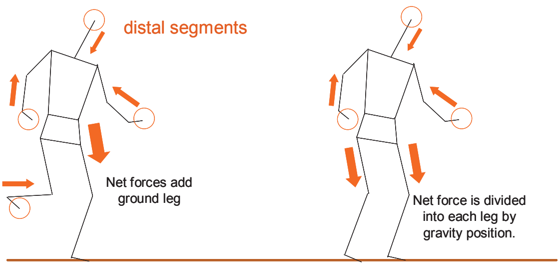

Figure 1: Motion patterns in walking.

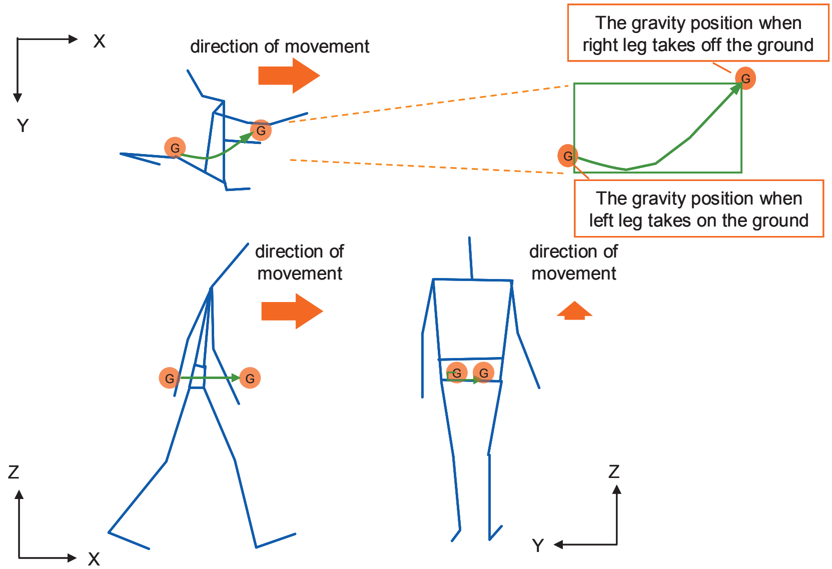

Figure 2: Behaviour of the body gravity position when both legs are on the ground.

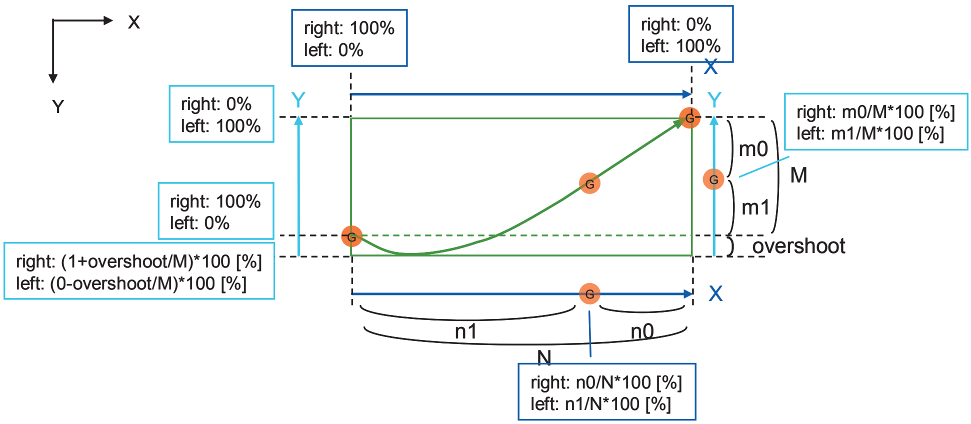

Figure 3: Determination of distribution of net force of each leg.

leg is 0% at the moment when left foot takes on the ground (initial gravity position in Figure 2). Likewise the distribution of the net force of left leg is 100% and that of right leg is 0% at the moment when right foot takes off the ground (final gravity position in Figure 2). So in this study the distribution of the net force is assumed to be determined with the rectangle on the XY plane that the trajectory of the gravity makes as shown in Figure 3.

In the X direction, the distribution of right leg is 100% and that of left leg is 0% in the initial position. On the other hand that of right leg is 0% and that of left leg is 100% in the final position. If the initial gravity position in X direction is assumed to be 0 and the final gravity position in X direction is assumed to be N, the distribution of right leg is $n_0 / N \times 100$ [%] and that of left leg is $n_1 / N \times 100$ [%] when the gravity position is n1 as shown in Figure 3.

Similarly, in the Y direction, if the initial gravity position is assumed to be 0 and the final gravity position is assumed to be M, the distribution of right leg is $m_0 / M \times 100$ [%] and that of left leg is $m_1 / M \times 100$ [%] when the gravity position is m1 as shown in Figure 3. However in Y direction, the gravity moves to the left after it moves to the right once. In this overshoot the

distribution of right leg is assumed to be $(1+overshoot/M)\times 100$ [%] and that of left leg is assumed to be $(0-overshoot/M)\times 100$ [%]. This overshoot is so small that it is not necessary to consider that the distribution of each leg becomes over 100% when combined with both X and Y directions.
So combined with both X direction and Y direction, the distribution of the net force of each leg was determined as follows. The effect of the lengths of N and M were considered because the longer the length, the greater the effect.

$$D_{right} = \frac{m_0 + n_0}{M+N} \times 100 \text{ [\%]}$$

$$D_{left} = \frac{m_1 + n_1}{M+N} \times 100 \text{ [\%]}$$

Walking experiments were conducted on three subjects to validate the suggested method. Each trial was recorded at 200 frames per second using a Vicon MX system with the ground reaction forces of each leg measured by separate force plates. The ground reaction forces were estimated with the suggested method and compared with the force plate data.

RESULTS AND DISCUSSION: The ground reaction forces for subject 1 as calculated by the proposed method (solid lines) and as measured by the force plates (dashed lines) are shown in Figure 4. Shaded areas indicate periods of double support. Stick figures above the graph show the approximate orientations of the limbs. The correlations between the calculated ground reaction forces and force plates of each axis are shown in Table 1.

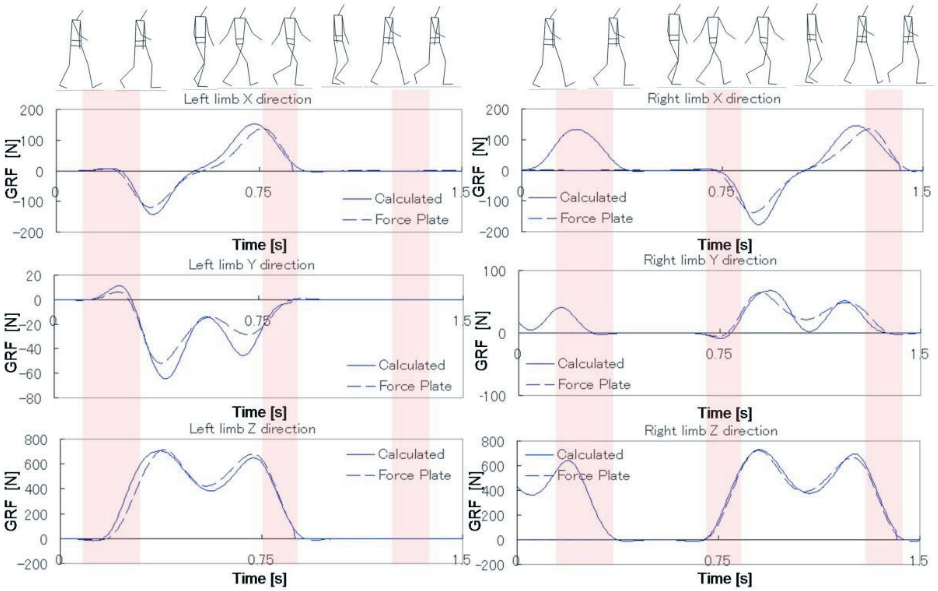

Figure 4: Ground reaction forces compared between the proposed method and force plates.

Figure 5 shows the net sagittal plane moments of force during one stance phase of both ankles as calculated by the proposed method (solid lines). In this figure, the positive direction indicates a plantiflexor moment; negative moments are dorsiflexor. In addition, Figure 5 shows the same moments calculated using measured ground reaction forces and distal-to-proximal inverse dynamics (dashed lines) compared to the estimated moments. The two sets of moments were in very close agreement except for a brief period during early stance for the left ankle.

Table 1
Correlations between the suggested method and force plates

	Left limb			Right limb		
Subject	X	Y	Z	X	Y	Z
1	0.98	0.97	0.92	0.97	0.93	0.99
2	0.99	0.94	0.96	0.98	0.94	0.98
3	0.95	0.95	0.99	0.96	0.96	0.98

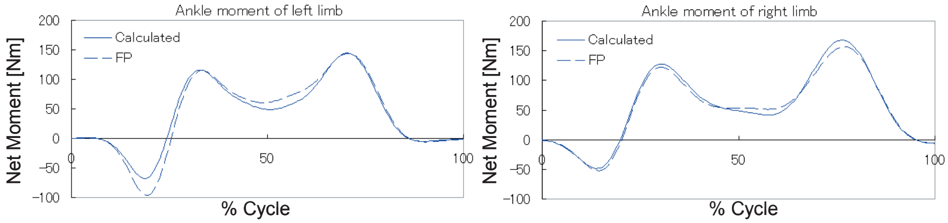

Figure 5: Net moment of ankle joint compared between the proposed method and the inverse dynamics.

The results show that the calculated ground reaction forces were almost the same as the data from the force plates. The differences between the calculated ground reaction forces and the force plates were a little large when one leg was on the ground. The reason for this is because the measurement errors of the joint positions were not negligible. When one leg is on the ground, some segments move faster than when both legs are on the ground. The accelerations of these segments may be quite different from their true values consequently the measurement errors are relatively larger. Thus, the calculated ground reaction forces may be different from the actual ones. However, the net moment of ankle joint calculated from the distal segment using the proposed method was almost the same as that from the measured ground reaction forces using inverse dynamics. Furthermore, strong correlations for the ground reactions showed that the suggested method was reasonably accurate.

CONCLUSION: This study demonstrated a way to calculate ground reaction forces throughout a walking cycle from video-captured data. Several walking trials were conducted to validate the proposed methods. Strong correlations between the calculated ground reaction forces and directly measured ground reaction forces showed that the proposed method was effective. This study permits the analysis of motions where it is difficult to use force plates. Furthermore, this study can contribute the advancement of computerized human models.

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