PAPER

Training Assist System of a Lower Limb Prosthetic Visualizing Floor-Reaction Forces Using a Color-Depth Sensing Camera

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SUMMARY Some unilateral lower-limb amputees, have through continued exertion, increase the foot reaction force of the sound leg. The asymmetric gait with a prosthetic leg may thus negatively affect the musculoskeletal health of the leg on the healthy side. Therefore, it is important for these amputees to learn how to adjust the balance of each foot load in training. The aim of this study is to develop a training support system visualizing floor-reaction forces using a color-depth sensor. The pose of the entire body of the amputee is measured by the depth sensor, and the floor reaction force is estimated based on Zero Moment Point (ZMP), which is calculated using the center of mass of the amputee. Evaluation experiments of the proposed method were performed and they confirmed the effectiveness of the estimation method and the training with the visualization of reaction force.

key words: rehabilitation, visualization, prosthetic leg, zero moment point

1. Introduction

If the weight load of the prosthetic limb is not heavy enough for some unilateral lower-limb amputees during gait, the load of the weight that the sound leg withstands increases gradually over time. Chronic pains may be elicited, including fatigue or lumbago, and joint diseases, including pes planovalgus or knee osteoarthritis.

Statistical analysis shows that the amputees consistently loaded the intact limb more than the prosthetic limb, regardless of its role during gait initiation, whether at stance or during swing [1]. Moreover, more joints and muscles of the affected limb are lost owing to higher-level amputations, the greater energy cost and a slower speed [2]. Therefore, it is important for the unilateral amputees to be provided with rehabilitation to balance the left and right weight loads. When the amputees with their prosthetics receive training on how to put load on the prosthetic limb, in most cases, physical therapists and prosthetists verbally instruct the patients on how to apply the weight load and on the method of loading the prosthetic limb verbally. Correspondingly, the patients with prosthetics adhere to their instructions based

on their self-image in a mirror located in the training room, whereby the therapists use two weight scales to instruct the learners to weigh each foot on each scale and adjust the weight load accordingly. The period of learning to walk with their prosthesis is short, and few amputees have the opportunity to be provided with training after social rehabilitation. Therefore, during the early stage of training, the learner's proper adjustment of the weight load of each foot has had an effect on "Activities of Daily Living (ADL)" and the "Quality of Life (QOL)".

The aim of this study is to improve the asymmetrical gait of the amputees and their QOL. Therefore, this work developed a training assist system based on visualizing the gait and weight load of each foot.

2. Training Assist System Visualizing Floor Reaction Force

Even though physical therapists and prosthetists instruct the learners using subjective terms, it is important for rehabilitators to show the learners the objective parameters, such as the physiological parameters and physical parameters. Additionally, training-assist systems visualizing objectively several of these parameters have been developed recently, and it is known that their effectiveness is confirmed in regard to the rehabilitation.

2.1 Past Research of Real-Time Visual Feedback

Dingwell et al. [3] developed the system for assessing and providing feedback of gait symmetry information in real time to participants walking on a motorized treadmill. The center of pressure shows a representation of this output display. Moreover, real-time visual feedback not only results in an immediate improvement in symmetry, but there are also concomitant reductions in heart rate and oxygen consumption while patients walk at a steady pace on a treadmill [4]. Davis then suggested that visual feedback rehabilitation may serve as a useful tool for amputee patients. Nakagawa et al. [5] developed a prosthetic gait training system that consisted of two load cells that were included in a parallel bar and in prostheses, and visualized the floor reaction forces.

The gait training system known as computer-assisted rehabilitation environment (CAREN) was effective in improving gait performance in a person with a unilateral transfemoral amputation [6]. The use of virtual reality (VR) en-

Manuscript received March 12, 2015.

Manuscript revised June 2, 2015.

Manuscript publicized July 28, 2015.

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DOI: 10.1587/transinf.2015EDP7089

vironment based on real-time feedback holds great promise for improving the rehabilitation of individuals with an amputation.

On the other hand, real-time visual feedback was shown to be effective in motor training for cerebral palsy. Sabe et al. developed the new visual feedback device, which measured the load that the patients exert on the handrails, and directly showed this load by using a display [7].

2.2 Visualizing Load Weight without Force Sensors

Based on literature [4], the visualization of the floor reaction force is important for the rehabilitation in gait with prosthesis. Therefore, the purpose of this study is the development of a rehabilitation-assist system that visualizes the floor reaction force in real time. However, three-dimensional optoelectronic motion-capture systems and force sensors are prohibitively expensive for clinics for introducing them in daily practice. Additionally, the learners with prosthetics need to use the devices with force sensors or load cells but the measurement area is limited. Gait training programs are prescribed to assist in the rehabilitation process of many clinical conditions. In these cases, low-cost and convenient systems without the need to use force sensors.

Recently, an inexpensive and convenient device that can measure the entire human pose was developed, and the device was used for the rehabilitation.

Clark et al. assessed the concurrent validity of kinematic data recorded using Microsoft's KINECT [8], during a gait retraining session [9]. Llorens et al. [10] presented a study involving chronic stroke patients for the evaluation of the clinical effectiveness of a virtual stepping exercise using skeleton tracking through the KINECT depth sensor. Kitsunezaki et al. [11] developed several applications that used KINECT for physical rehabilitation tests, such as walking motion and joint range, and confirmed the effectiveness of these applications.

The color-depth sensor (KINECT) can extract the entire body pose of a human, so a method to estimate the floor reaction force using the depth data is proposed in this study.

3. Estimating Floor Reaction Force Based on Entire Pose Information

When human stands still or walks without a hand reaction force from an environment, an external force from only feet is exerted on the human only from the feet. Therefore, this floor-reaction force equals the inertia force of entire body. This floor reaction force can then be estimated using the time-series data of the pose information of the entire body.

However, the human body is a complex and nonlinear multi-link structure. Therefore, to estimate the floor reaction force in real-time, a calculation method based on a simple dynamic model is proposed in this study.

The outline of the proposal method is shown in Fig. 1. This human body is treated as the simple dynamic model, and the floor-reaction force is estimated based on the model.

Fig. 1 Mechanism of the proposed system where the floor reaction forces are estimated based on a simple dynamic model.

The detailed algorithm is explained in 3.1 and 3.2.

3.1 Simple Dynamic Model

Vukobratovic [12] specified a zero moment point (ZMP) with respect to which the dynamic reaction force at the contact of the foot with the ground does not produce any moment in the horizontal direction, and constitutes the point where the total of horizontal inertia and gravity forces equals zero [13].

This ZMP utilized a pattern generator and a stabilization controller of the bipedal locomotion robot [14]–[16]. It is known that the motion of the humanoid robot based on the walking pattern generator with the ZMP dynamic model is similar to the motion of the human [17]. Therefore, the ZMP dynamic model may represent a part of the human walking motion. In the cases, where the human body is approximated as a simple mass model. The ZMP is represented by Eq. (1).

$$\begin{cases} p_x = \frac{Mgx + Mp_z\ddot{x} - M(z\ddot{x} - x\ddot{z})}{Mg + M\ddot{z}} \\ p_y = \frac{Mgy + Mp_z\ddot{y} - M(y\ddot{z} - z\ddot{y})}{Mg + M\ddot{z}} \end{cases} \quad (1)$$

where (x, y, z) denotes the Center of Gravity (COG) position, M is the mass, g is the acceleration due to gravity, (p_x, p_y) is the ZMP position. If $p_z = 0$, Eq. (1) leads to Eq. (2), known as the ZMP equation.

$$\begin{cases} p_x = x - \frac{z}{\ddot{z} + g}\ddot{x} \\ p_y = y - \frac{z}{\ddot{z} + g}\ddot{y} \end{cases} \quad (2)$$

From Eq. (2), the human body consisted of multi-link structure is represented as simple dynamic model that has only the COG and the ZMP. The COG of the entire body is calculated by the COG position of each body segment, which is calculated based on the literature [18].

3.2 Calculating Floor-Reaction Force Components

The aim of this paper is to visualize each foot-reaction force. Therefore, only the dynamic model on the lateral plane is treated, and the dynamic model of the x-axis is omitted in this section.

The ZMP can be calculated by the floor-reaction force and the position of each foot represented by Eq. (3).

$$p_y = \frac{f_R y_{Rf} + f_L y_{Lf}}{f_R + f_L} \quad (3)$$

where f_R is the floor-reaction force of the right foot, f_L is the reaction force of the left foot, y_{Rf} is the position of the right foot, and y_{Lf} is the position of the left foot.

The values of y_{Rf} and y_{Lf} can be obtained from the color-depth sensor and p_y can be calculated based on Eq. (2). However, f_R and f_L are unknown parameters. Therefore, another constraint equation is needed to be set.

The sum of each of the reaction forces equals the inertia of COG. The constrained condition is then set in accordance to the following equation Eq. (4).

$$f_R + f_L = F \quad (4)$$

where $F = M(g + \ddot{z})$. Corresponding, f_R and f_L are specified based on Eq. (5), which in turn is based on Eq. (3) and Eq. (4).

$$\begin{cases} f_R = \frac{p_y - y_{Lf}}{y_{Rf} - y_{Lf}} F \\ f_L = \frac{-p_y + y_{Rf}}{y_{Rf} - y_{Lf}} F \end{cases} \quad (5)$$

The position of each joint can be obtained by the color-depth sensor. However, the acceleration of each body segment is needed to calculate the ZMP.

Both y and z are discretized to allow calculation of $\ddot{y}$ and $\ddot{z}$ based on Eq. (6).

$$\begin{cases} \ddot{y} = \frac{y(i) - 2y(i-1) + y(i-2)}{T^2} \\ \ddot{z} = \frac{z(i) - 2z(i-1) + z(i-2)}{T^2} \end{cases} \quad (6)$$

where T is the sampling time and i is the time ($i = 2, 3, 4, \dots$).

3.3 Integrated Value of Floor-Reaction Force

When the learners stand still, they can adjust the floor-reaction force of each foot using the visual feedback, however, during the stepping and walking motion, the reaction forces rise and fall frequently. It is then difficult for the learners to control the force in real time. To understand the floor-reaction forces in real time, it may be effective to show the parameters changing incrementally on the display.

Therefore, integrated values of each foot-reaction force

Fig. 2 Flow chart indicating the calculation of the integrated values of each foot reaction force.

Fig. 3 Display example of the proposed visualization scheme using a color-depth sensor.

are calculated and displayed in real time. The integrated value of the left foot-reaction force is I_L , and the integrated value of the right foot-reaction force is I_R . If f_L is larger than f_R , I_L is incremented by $f_L - f_R$. The flow chart of the algorithm used to calculate the integrated values is shown in Fig. 2.

The display example of visual feedback is shown in Fig. 3. The green lines are the pose of the entire body, the blue circle is the position of the COG, the yellow line is the left reaction force, the magenta line is the right reaction force, the blue line is the integrated value of the left foot, and the cyan line is the integrated value of the right foot. The color data of the camera sensor is displayed as the mirror-reversed image.

4. Verification Experiments

To verify the effectiveness of the proposed method, verifi-

Fig. 4 Overview of the verification experiments.

cation experiments tested on healthy persons and the unilateral leg amputees were performed. In these experiments, the COG and ZMP calculated using the color-depth sensor and the floor-reaction forces were compared against data calculated by an optical motion capture system and force plates. Moreover, the effectiveness of the visual feedback using the proposed system was also verified.

4.1 Experimental Conditions

The overview of the experiments is shown in Fig. 4. The KINECT (Microsoft) and the color-depth sensing camera are used to estimate the floor-reaction forces, and the color image data and the floor-reaction forces are shown by the projector. The joints of the entire body are calculated based on the KINECT software developer kit (SDK) [8]. To evaluate the calculation result, the motion data of each participant is measured using the optical motion capture system (motion analysis) and force plates (KISTLER Co. Ltd.).

The participants were six healthy persons and the three unilateral leg amputees, including two trans-tibial amputees and one trans-femoral amputee. The study procedures were approved by the National Rehabilitation Center for Persons with Disabilities Institutional Review Board, and informed consent was obtained from all the participants. In this paper, only parts of the acquired data is processed and presented.

The measurement tasks are “static standing”, “stepping motion”, and “walking motion” without and with visual feedback. “Static standing” is when the participant keeps standing still for about half a minute. “Stepping motion” is when the participant marches in place for about half a minute. “Walking motion” is when the participant walks about three meters at his/her usual pace for five times.

In the experiments without visual feedback, the participants are instructed to perform each task in a normal way, and in the experiments with visual feedback, the participants are instructed to equalize the left and right floor-reaction forces.

The visualization example where the trans-femoral am-

Fig. 5 Snapshots of the trans-femoral amputee as he stepped at locations.

putee stepped at places is shown in Fig. 5. The floor-reaction forces are varied in accordance to the “stepping motion” of the participant, and the right or left force decreased with increases in the other force.

4.2 Verification of Force Estimation Method

To evaluate the proposed method, the estimated floor-reaction forces of the two healthy participants are shown in Fig. 6 (participant A) and Fig. 7 (participant B). (a) is the calculation result from the force plates, and (b) is the calculation result from the depth-sensing camera.

Comparing the calculation results from the force plates and the depth-sensing camera, the timing of the increase of each floor-reaction force, and the cycle of the trajectories based on the force plates are coincident with the cycle of the calculation results elicited by the proposed method. However, based on Fig. 6(b), the calculation result from the depth-sensing camera yields a steady error. In addition, these trajectories did not decrease to zero.

To analyze the results for which the floor-reaction forces yield the steady error based on the proposed method, the calculated COG trajectories and the ZMP trajectories of the participant A were used as shown in Fig. 8 and Fig. 9, respectively..

From Fig. 8, each COG trajectory calculated by the depth-sensing camera is coincident with the trajectories calculated by the motion capture system, and therefore the numerical error of the COG position is sufficiently-small. On

Fig. 6 Comparisons of the (a) calculation results from the force plates, and (b) calculation results from the depth-sensing camera. These are the results of the participant A.

Fig. 7 Comparisons of the (a) calculation results from the force plates, and (b) calculation results from the depth-sensing camera. These are the results of the participant B.

the other hand, from Fig. 9, the error between the ZMP calculated by the depth-sensing camera and the ZMP calculated by the force plates is large when the real ZMP moves to the contact area of each foot. The ZMP is calculated based on the COG position and the COG accelerations are approximated by Eq. (6), yielding the calculation errors of ZMP. Therefore, the floor-reaction forces calculated by the proposed method include the steady error.

These estimation results are associated with the steady error, but the increases and decreases of the right and left floor-reaction forces can be sensed fully. In these cases,

Fig. 8 Calculation results of the center of gravity along the x, y, and z axes using the motion capture system and the color-depth sensing camera.

Fig. 9 Estimation results of the zero-moment point on the y-axis using force plates and a depth-sensing camera.

these errors are not important for the feedback visualization of the training.

4.3 Verification of Visualization of Feedback Training

To verify the effectiveness of the visualization of the feedback training using the proposed method, the amputees adjusted both floor-reaction forces with visual feedback. The experimental results in the case of the trans-femoral amputee under “static standing” are shown in Fig. 10. Figure 10 (a) and (c) depict the actual reaction forces, and Fig. 10 (b) and (d) are the estimated reaction forces. Figure 10-(a) and (b) are the results without visualization, and Fig. 10-(c) and (d) are the results with visualization.

From Fig. 10 (a) and (b), the left reaction force is larger than the right force, and this particular participant wore the

Fig. 10 Evaluation of the effectiveness of the real-time visual feedback using the proposed sensing system for the amputee patient.

right trans-femoral prosthetic limb. This implies that the load of the prosthetic limb was not applied properly. Moreover, the trajectories of the estimated reaction force are similar to the trajectories of the actual reaction force. From Fig. 10(c) and (d), both left and right reaction forces converged at about the 400[N], and the participant could thus adjust the left and right reaction forces with the proposed visual feedback training system.

These results have shown that the proposed training system can assist the amputees to train to adjust the floor-reaction forces.

4.4 Integrated Value Results

To assess on whether the integrated value of the floor-reaction force is useful for the lower limb prosthetic training, the integrated floor-reaction forces of the “stepping motion” of the trans-femoral amputee were calculated, and these experimental results are shown in Fig. 11. Figure 11(a) depicts the estimated reaction forces, and Fig. 11(b) the integrated values of the floor-reaction forces.

From Fig. 11(a), the reaction-force of the left foot, that is the unaffected leg, is slightly larger than the right leg that is the prosthetic leg. The walking cycle is about 1.0[s]. Therefore, it may be difficult for the learner to adjust the reaction force with visual feedback. On the other hand, from Fig. 11(b), the gap between the left and right reaction forces widened after about fifteen seconds, and the learner could understand the difference between the load of the sound leg and the prosthetic leg.

In this paper, the effectiveness of the visual feedback training using the integrated reaction force was not verified. This verification experiment will be tested in the future.

Fig. 11 Computation results of (a) floor-reaction forces, and (b) integrated forces using the proposed algorithm by the participant with a trans-femoral prosthesis.

5. Conclusion

Some amputees walk with an asymmetrical gait, which may lead to future musculoskeletal degenerative pathologies. Therefore, the rehabilitation that instructs someone how to properly accommodate each foot-reaction force is needed. In this study, the training-assist system visualizing floor-reaction forces was developed and used to verify the effectiveness of the proposed system, and the verification experiments using the integrated value is future work. This training system can visualize the floor reaction force of the amputees using a depth-sensing camera. Given that this system did not use force sensors, it has a low cost and it is convenient. Based on verification experiments, even though the floor-reaction forces had steady errors, the amputees can adjust each floor reaction force using real-time visual feedback, thereby confirming the effectiveness of the proposed method.

In this paper, the training system that visualized floor-reaction forces was developed. On the other hand, several musculoskeletal parameters may be more useful for improving the asymmetrical gait. System visualization of several human musculoskeletal data, such as muscle tension information [19], will be collected in future work.

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