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A KINEMATICAL AND KINETICAL ANALYSIS ON THE SWING PHASE OF AMPUTEE GAIT

Yuji OHGI[1], James Bruce LEE[2] and Koichi KANEDA[3]

[1]Graduate School of Media and Governance, Keio University, Fujisawa, Kanagawa, Japan

[2]Center for Wireless Monitoring and Application, Griffith University, Brisbane, Australia

[3]Faculty of Engineering, Chiba Institute of Technology, Narashino, Chiba, Japan

The authors investigated the swing phase of the transfemoral and transtibial amputees by using optical motion capture system. The thigh, shank foot were modeled as a three-linked rigid segment model. Kinematical parameters, such as joint angle, angular velocity/acceleration and linear acceleration of the center of mass were also calculated by the obtained coordinates of the anatomical landmark markers. Using the inverse dynamics, the kinetical parameters, such as the joint force and torque acting at each joint were calculated. The authors focused on the initiation of the swing phase caused by the force at both the hip and knee joints. In addition, the relationships between the internal/external rotation and the abduction/adduction of the lower extremity during the swing phase was also discussed in this study.

KEY WORDS: amputee gait, transfemoral and transtibial amputee, inverse dynamics

INTRODUCTION: A transfemoral amputee cannot control their swing motion because of the nonexistence of muscular power at the knee joint. For the compensation of this malfunction, a couple of mechanism which can control the swing phase of the transfemoral amputee gait has been developed, such as the Coulomb's frictional and the air or oil damping knee joints. However, naturally, the transfemoral prosthesis can be modeled as the double pendulum without voluntary torque input at the knee joint (Mena D., et al., 1981). This means that, in order to propel their shank forward without muscular power in the swing phase, the transfemoral amputee must apply their joint force to the shank at the knee. This muscular independent pendulum mechanism is natural in some senses, because no muscular power is necessary for the motion. Yamazaki et al. modeled lower extremity as the double pendulum in the sprint running and analyzed knee joint power (Yamazaki N., et al., 2012). They reported that the dominant power source of the shank is the joint force not the muscular torque in the swing phase. In addition, they suggested that the hip acceleration, namely the joint force at the hip, which is caused by the landing motion of the opposite leg makes the initiation of the swing of the lower extremity. This mechanism of the swing motion without muscular power and the motion initiated by the opposite side leg motion is believed to be natural and beneficial for the transfemoral amputees. Similar advocacies were claimed in some previous studies (Mena D et al., 1981, Seroussi R. E., et al., 1996). Up to date, an assessment of desirable or undesirable motion of the swing phase are judged only by the physical therapist or Prosthetist and Orthotist with their subjective decision.
The authors have been developed and applied embedded tiny inertial sensor devices for the movement analysis on the sports and used them for the skill assessment (Ohgi, et al., 2012). The purpose of this study was to obtain fundamental temporal, kinematical and kinetical parameters to assess the swing phase of the transfemoral amputee gait for the future inertial sensor application.

METHODS: One transfemoral (female 153cm, 52Kg, 52yrs), two transtibial amputees (male 169cm, 64Kg, 48yrs, female 148cm, 49Kg, 67yrs) participated in this study. All of subjects provided a written informed consent to participate in this study and their health status was

examined before each subject's experiment. The ethics committee in Shonan Fujisawa Campus, Keio University approved this study.
A 15m walking pathway which was covered by the 11 optical motion capture cameras (Natural Point Ltd.,VR100R2) was settled up for our experiment. The subjects walked 10 times at the three different self-defined speed conditions, such as slow, middle and fast. 28 passive reflective markers were attached on the subject's anatomical landmarks with their torso and lower extremities. Obtained marker coordinates were labeled and interpolated by VENUS3D software (Nobby Tech Ltd.), then analyzed by Mathematica 8.0 (Wolfram Research Inc.). High frequency components of the obtained marker coordinates were smoothed by using Hodrick-Prescott filter with its gain at 1000.0. The authors hypothesized that the lower extremity is the triple pendulum. Mass and moment of inertia of intact limb for the amputee subjects and the able-bodied subjects were estimated by Chandler's equations (Chandler, R.F., 1975). As for the prosthetic limb, those of socket, knee joint, shank pipe and foot parts were directly measured by the oscillation method. Unknown parameter, mass and moment of inertia of the stump were supposed to be proportional to the residual part volume of the thigh.

RESULTS: The authors calculated the temporal parameters and its bilateral symmetry, such as timing of HC, HO, TO, etc. and duration of both the stance and the swing phases at each speed condition. The local coordinate system on the each segment was defined according to the ISB recommendation (International Society of Biomechanics 2002). Then, for the kinematical parameters, the velocity and the acceleration of the segment CG and the angle between segments, the angular velocity/acceleration of each segment were obtained. For the kinetical parameters, the joint force, moment and power were calculated by the Newton-Euler method.

$$m_i(\ddot{x}_i - g) = \sum F_i$$
$$J_i\dot{\omega}_i + \omega_i \times (J_i\omega_i) = \sum \tau_i$$

where m_i and J_i are the mass and the moment of inertia of segments. x_i is the displacement of the center of mass of the segment. w_i is the angular velocity of the segment. F_i is the external force acting on the segments. t_i is the muscular torque at the joint.

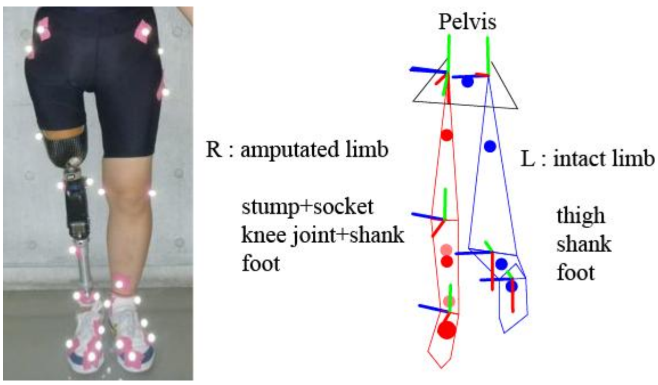

Figure 1: A transfemoral amputee subject and reflective markers (left). A schematic illustration of the inverse dynamics calculation for the three-linked segment model (right).

Figure 2 shows the time history of the knee angle during the swing phase by the transfemoral amputee subject who had been installed NK-6 Legarto (Nabtesco, Co) for her knee joint. Although the prosthetic knee only shows its flexion-extension change, the intact knee does other two rotational motion, such as internal-external rotation and abduction-adduction. This means that intact limb/joint has more degree of freedom rather than mechanical artificial knee joint.

DISCUSSION: In our experimental condition, since there was no force platform for the trial, the authors concentrated on the forward motion of the shank during the swing phase and its initiation caused by the thigh and pelvis movement. Since the transfemoral amputee does not have any voluntary torque at the knee joint. Only the decelerating torque by the frictional or air/oil damper force was applied. Therefore, the forward shank swing motion requires the joint force at the knee. In addition, we also investigated the internal/external rotational motion of the shank or interlocked whole lower extremity during the swing phase.

There has been common understanding that a difficulty exists on the transfemoral amputees to walk slowly. For such a situation, they have to pull and abduct their lower extremity at the beginning of the swing, because of the lack of the acceleration of the pelvis, in other words, the joint force at the hip. Theoretically, the forward swing with abduction makes external rotation by the gyro effect. We can see this effect so-called Coriolis force in the Euler equation, $w' \ (Jw)$, which makes unexpected rotational motion depending on the combination of inertia tensor and the angular velocity. Although, the relationships between internal/external rotation and the abduction/adduction motion of the lower extremity are complicated, the quantitative analysis makes it distinguish the rotational motion with or without voluntary muscular torque at the hip. This quantitative information on this voluntary/involuntary rotational lower extremity motion will be beneficial for both the subjects and the Prosthetists in the rehabilitation.

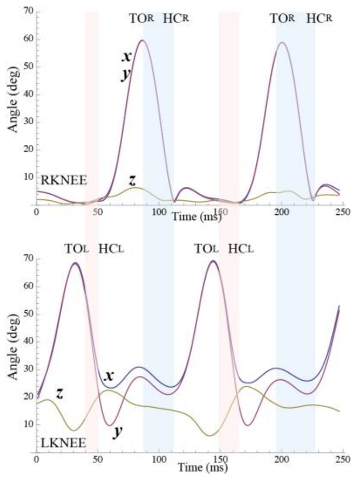

Figure 2: Three dimensional angles of knee joint by the transfemoral amputee subject. Right toe off (TOR), right heel contact (HCR) indicate the swing phase of the right limb. Also left toe off (TOL), left heel contact (HCL) indicate the swing phase of the left limb.

CONCLUSION: The authors quantified the joint force at both the hip and the knee joints in the swing phase by the amputee gait, which makes shank move forward. In addition, the internal/external rotation and the abduction/adduction of the shank and/or interlocked lower limbs as the function of the motion dependent effect. The results of this study showed that kinematical and kinetical analysis distinguish the voluntary or involuntary internal/external rotational motion of the lower extremity during the swing phase.

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