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A Study of the Effect of the Femoral Head Diameter on Prosthetic Hip Joint Dislocation Using a Hip-Joint Motion Simulator

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Abstract—**Prosthetic hip joint dislocation phenomenon is generated by the hip joint simulator and the effect of the femoral head diameter is studied under the same condition which is similar to the condition in daily activities. Impedance control is applied to control the hip joint motion and the joint contact force simultaneously in order to take into account the constraint caused by surrounding tendons, muscles, and a joint capsule of the hip joint. The experimental results show that the hip joint dislocation phenomenon is generated by the simulator and the obtained results about the effect of the femoral head size agree with those of the other research.**

I. Introduction

TOTAL hip arthroplasty (THA) is often carried out for the patients who suffer from rheumatoid arthritis or osteoarthoritis to remove pains and improve their motion functions. However, incidence of dislocation is one of the most serious problems to be overcome after the THA [1]-[5]. In order to overcome the problem of dislocation, mechanism of dislocation must be analyzed. It is known that the size of the femoral head [2]-[4] and total anteversion (cup and stem) [5] affect the risk of dislocation. It is important that the evaluation for the risk of dislocation is performed under the same condition, although in-vivo studies are performed under different condition because of the personal difference. A hip joint simulator has been developed to study the mechanism of dislocation, microseparation, and wear [6]-[8]. Evaluation of the performance of prosthetic hip joints can be carried out under the same condition using the hip joint simulator.

In this study, prosthetic hip joint dislocation phenomenon is generated by the hip joint simulator and the effect of the femoral head diameter is studied under the same condition which is similar to the condition in daily activities. Impedance control is applied to control the hip joint motion and the joint contact force simultaneously in the simulator in order to take into account the constraint caused by tendons, muscles, and a joint capsule. Ordinal daily hip joint motion, which might induce dislocation, is generated by the hip joint simulator. Three kinds of femoral head (ϕ26, ϕ32, and ϕ40) are prepared for the experiments to investigate the effect of femoral head diameter on dislocation under the same condition. The experimental results show that the hip joint dislocation phenomenon is generated by the simulator and the obtained results about the effect of the femoral head size agree with those of the other research [2]-[4] in which the effect of the femoral head size was studied.

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II. Hip Joint Motion Simulator

In order to generate hip joint motion and hip joint contact force simultaneously, a 7DOF hip joint simulator has been developed [6],[7]. Figure 1 shows the developed hip joint simulator. The simulator consists of a DC motor [RHS-32-6030-E124AL, Harmonic Drive Systems Inc.], a femur link, six linear actuators (a 6DOF parallel link mechanism) [883 series, Moog Japan Ltd.], a platform, a 6-axis force sensor [IFS-65E20A400-I100-EX, Nitta Co.], a prosthetic hip joint, universal joints, 3-DOF passive joint units, and a base frame. The prosthetic hip joint consists of a stem, a femoral head, and a cup. The prosthetic hip joint is

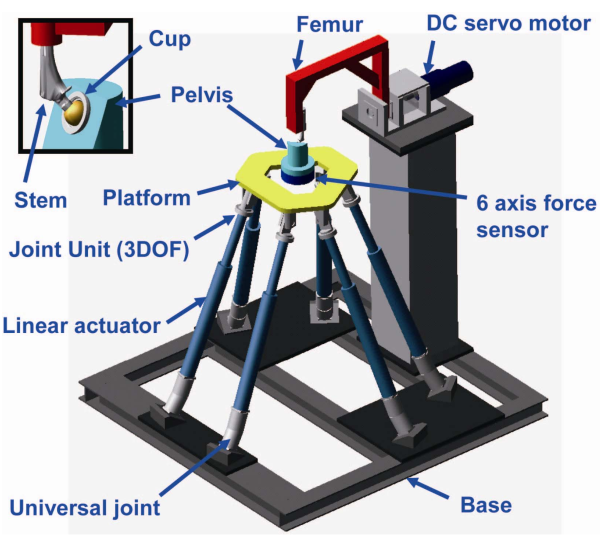


Fig. 1. Hip joint simulator.

installed upside-down in this simulator, so that the femur side is placed above the pelvic side.

Since wide movable range (i.e., 135 degrees in flexion and 20 degrees in extension) is required for the hip joint flexion/extension motion, the DC motor is in charge of generating the hip joint flexion/extension motion in the simulator. The parallel link mechanism is in charge of generating the adduction/abduction motion (i.e., 20 degrees in adduction and 45 degrees in abduction) and the internal/external rotation motion (i.e., 45 degrees in internal rotation and 45 degrees in external rotation) as well as the hip joint contact force (i.e., the contact force between the cup and the femoral head). A touch sensor is attached on the brim of the cup, so that the impingement of the stem with respect to the cup can be detected.

The dynamic equation of the 6DOF parallel link mechanism is written as:

$$\tau = M(q)J_{2x}(\ddot{x} - \dot{J}_x^{-1}\dot{q}) + h(q,\dot{q}) + F_c \ \mathrm{sgn}(\dot{q}) + J_{2x}^{-T} f_d + g(q) \quad (1)$$

where τ is the torque vector of the linear actuators, q is the position vector of the linear actuators, $M(q)$ is the inertia matrix, $h(q,\dot{q})$ denotes the Coriolis and centrifugal components, F_c represents the Coulomb friction of the linear actuators, J_x stands for the Jacobian relating the platform velocities and the angular velocities of the linear actuators, J_{2x} stands for the Jacobian relating the velocities the cup center and the angular velocities of the linear actuators, f_d is the desired hip joint contact force, and $g(q)$ represents the gravity.

The simulator is able to generate any possible condition of the hip joint motion and the joint contact force. PD control is applied for the DC motor to make hip flexion/extension motion. Impedance control is applied for the 6DOF parallel link mechanism to control the other hip joint motion and the joint contact force using the force sensor in order to take into account the constraint caused by tendons, muscles, and a joint capsule. The equation of the desired impedance characteristics is written as:

$$M_d \ddot{x} + B_d(\dot{x} - \dot{x}_d) + K_d(x - x_d) = f \quad (2)$$

where M_d is the desired inertia matrix, B_d is the desired damping matrix, and K_d is the desired stiffness matrix. In this study, the diagonal components of M_d, B_d, and K_d for translational displacement are defined as 1.5, 4,000, and 850,000, respectively.

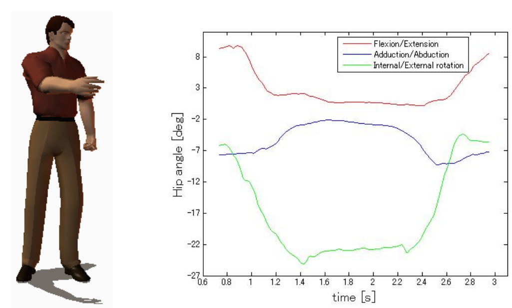
III. DISLOCATION

Dislocation of the hip joint is a phenomenon that the femoral head comes out from the cup. One of the main reasons of the prosthetic hip joint dislocation is that the stem (especially the collar part) comes in contact with the cup or the pelvis at the unexpected point and then generates the impingement force to push the pelvis away during the hip joint motion. In this study, the posterior dislocation which occurs when the hip joint flexion angle exceeds the movable range limit and the anterior dislocation which occurs when the hip joint extension angle exceeds the movable range limit are generated by the simulator.

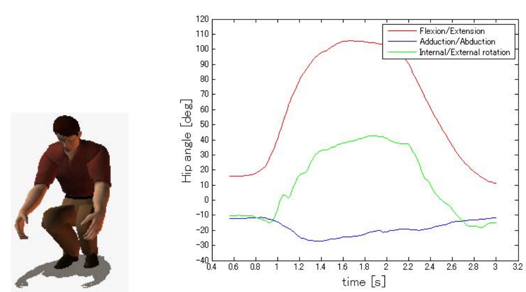
When the hip joint motion is continued even after the impingement, the femoral head goes out of the cup because of the leverage. We assume that the dislocation phenomenon have been started if the location of the femoral head center is shifted from the cup center. Since impedance control is applied the femoral head tends to come back into the cup if the impingement is disappeared. This effect is similar to the constraint caused by the surrounding tendons, muscles, and a joint capsule of the hip joint. Note that the desired hip joint contact force during the hip joint motion is defined as 10 N in this study.

IV. EXPERIMENT

Two kinds of daily hip joint motions are generated by the simulator in the experiment. One is the motion which might induce the anterior dislocation (Fig. 2 (a)) and the other is the motion which might induce the posterior dislocation (Fig. 2 (b)). Three kinds of femoral head (ϕ26, ϕ32, and ϕ40) are prepared for the experiment (Fig. 3). An exclusive cup is prepared for each femoral head. The external size of each cup is the same although the internal size is different. The cup anterior opening angle is set to 0 or 40 degrees, the cup lateral opening angle is set to 45 degrees, and the stem anteversion angle is set to 0 or 40 degrees in the experiment (Fig. 4). Every combination (Table I) of these conditions is performed in the experiment to investigate the effect of femoral head diameter on dislocation under the same condition.



(a) inducing the anterior dislocation.



(b) inducing the posterior dislocation.

Fig. 2. Daily hip joint motion captured by VICON motion capture system.

TABLE I
EXPERIMENTAL CONDITION

No. of Patterns	Condition	Details
2	Daily motion	1: motion inducing the anterior dislocation 2: motion inducing the posterior dislocation
3	Femoral head	1: ϕ 26, 2: ϕ 32, 3: ϕ 40
2	Anterior opening angle of the cup	1: 0 degree 2: 40 degrees
1	Lateral opening angle of the cup	1: 45 degrees
2	Anteversion angle of the stem	1: 0 degree 2: 40 degrees

As a result, the anterior dislocation occurred under the condition that the cup anterior opening angle was set to 40 degrees, the cup posterior opening angle was set to 45 degrees, and the stem anteversion angle was set to 40 degrees. The posterior dislocation occurred under the condition that the cup anterior opening angle was set to 0 degree, the cup posterior opening angle was set to 45 degrees, and the stem anteversion angle was set to 0 degree.

The experimental results of the anterior dislocation are shown in Fig. 5. The results with the femoral head of ϕ26, ϕ32, and ϕ40 are shown in (a), (b), and (c), respectively. The dislocation phenomenon began when the amount of the hip joint contact force started to increase (i.e., when the impingement occurred). The experimental results of the posterior dislocation are shown in Fig. 6. The results with the femoral head of ϕ26, ϕ32, and ϕ40 are shown in (a), (b), and (c), respectively. In these experiments also, the dislocation phenomenon began when the amount of the hip joint contact force started to increase (i.e., when the impingement occurred).

Fig. 3. Femoral heads and cups (JMM Co.).

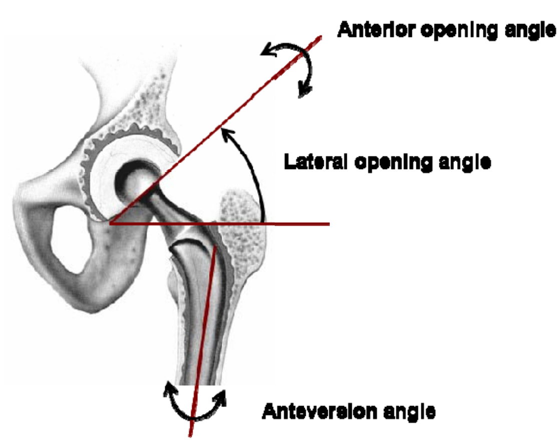
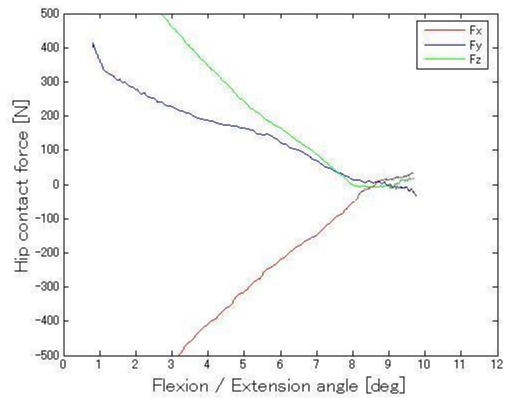


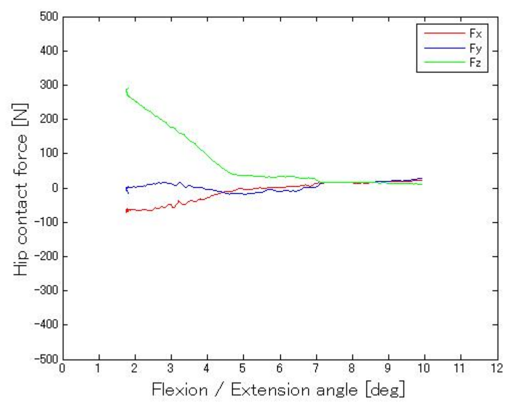
Fig. 4. Angles of prosthetic hip joint

V. DISCUSSION

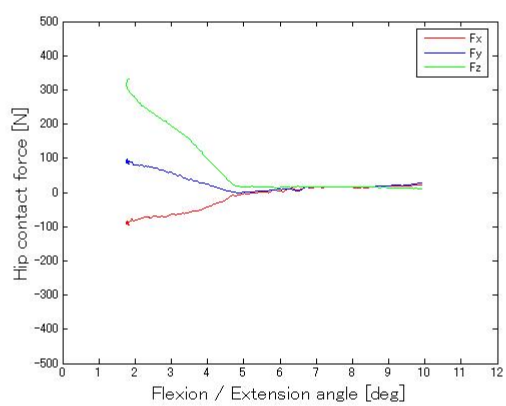
In the case of the anterior dislocation shown in Fig. 5, dislocation occurred when the hip flexion/extension angle is around 8 degrees with the femoral head of ϕ26, 6 degrees with the femoral head of ϕ32, and 5 degrees with the femoral head of ϕ40 during hip joint extension motion. This means, if the



(a) femoral head: ϕ26.



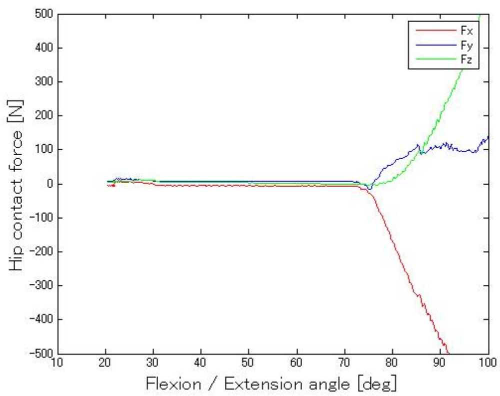
(b) femoral head: ϕ32



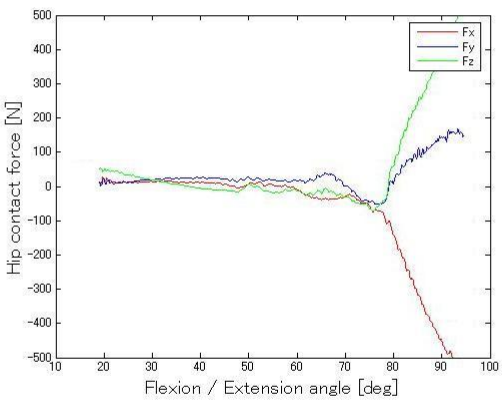
(c) femoral head of ϕ40

Fig. 5. Experimental results of the anterior dislocation.

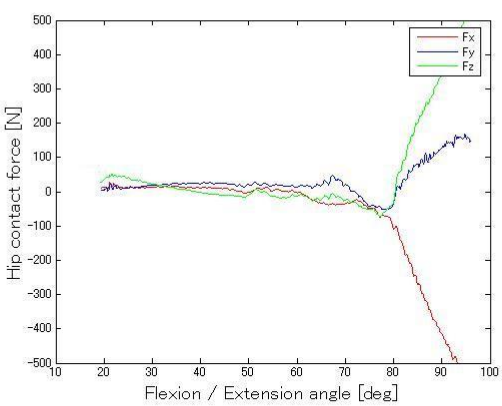
size of the femoral head becomes larger, the hip joint extension angle becomes larger. In the case of posterior dislocation shown in Fig. 6, dislocation occurred when the hip flexion/extension angle is around 75 degrees with the femoral head of ϕ26, 77 degrees with femoral head of ϕ32, and 79 degrees with the femoral head of ϕ40 during hip joint flexion motion. This also means, if the size of the femoral head becomes larger, the hip joint flexion angle becomes larger. These tendencies agree with the results of the other research [2]-[4] in which the effect of the femoral head size is studied. Consequently, it can be confirmed that the effect of the femoral head size with respect to the dislocation during the daily motions agreed with those of the other research [2]-[4].



(a) femoral head: ϕ26.



(b) femoral head: ϕ32



(c) femoral head of ϕ40

Fig. 6. Experimental results of the posterior dislocation.

VI. CONCLUSION

Prosthetic hip joint dislocation phenomenon during the daily hip joint motion has been generated by the hip joint simulator and the effect of the femoral head diameter has been studied under the same condition which is similar to the condition in daily activities which might induce the hip joint dislocation. The experimental results showed that the obtained results about the effect of the femoral head size agreed with those of the other research.

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