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Letters:

Motion performance and impingement risk of total hip arthroplasty with a simulation module*#

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The present study introduced a new motion analysis method for total hip arthroplasty (THA). A motion simulation module of THA was designed and developed, which can simulate the THA's implantation condition and motion and detect the theoretic range of motion (ROM) before the prosthetic component impingement happens. The impingement risk of THA should be investigated through comparing the analysis data of module with the realistic kinematics obtained from hip motion measurement. Furthermore, in order to demonstrate how to use this module, the kinematic data of the hip were recorded by measuring the lower limbs motion of general population in six activities of daily living (ADLs), i.e., kneeling, squatting, ascending stair, descending stair, walking, and jogging. Analysis results showed that the possibilities of impingement and dislocation were larger during the squatting activity. It is reasonable to believe that the motion simulation module of THA in the present study is helpful for clinical medicine engineering, and hip implant design and optimization.

Impingement has presented a high occurrence rate since THA has been wildly applied in clinic, and does great harm to patients (Yoshimine and Ginbayashi, 2002; Brown and Callaghan, 2008; Kessler *et al.*, 2008; Tanino *et al.*, 2008; Patel *et al.*, 2010). The study on the subjects of the impingement and dislocation of THA has attracted scientists and doctors' attention. There are various factors that increase the propensity of impingement or dislocation; except the patients themselves, factors that we cannot choose, the clinical factor and hip implant design are the main factors. In the clinical factor, inappropriate selection of the implant option has a great chance to lead to cup/neck impingement or dislocation. As well, poor alignment of implants for individual patient also leads to serious consequences which depend on three implantation parameters: femoral anteversion, acetabular anteversion, and acetabular inclination (Ji *et al.*, 2010). In implant design, impingement is also related with four design parameters: neck design, head-neck ratio, stem-neck angle, and cup opening plane design (Ji *et al.*, 2010). In fact, these major factors are in direct linkage with human lower limb activity. If the realistic hip motion requirement of some activities is far more than the theoretic ROM provided by THA, then cup/neck impingement or dislocation will be bound to occur.

In the present study, we used a 3D parameterized motion simulation module of THA to investigate THA's motion performance and impingement risk. All the implantation and design parameters mathematically influencing the theoretical ROM were involved. The module can easily imitate the implant environment of THA, simulate the motions of implants, and detect the maximum ROM before the cup/neck impingement happens. Furthermore, in order to demonstrate how to use this module, the

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realistic hip kinematic data of general population in six ADLs were obtained from human lower limb activity measurement. By comparing the theoretic results of the motion simulation module with measured kinematic data, we investigated the relationship between the cup/neck impingement and ADLs, and find the most risky activity that results in the prosthetic impingement or dislocation.

Due to the fact that just the motion of the hip is discussed in the current study, only the kinematic curves of the hip are listed, as illustrated in Fig. 1. The realistic ROMs of the hip in six ADLs are shown in Table 1. These kinematic data suggested that all six activities were relevant with hip flexion. The activity with the maximum flexion range was squatting; on average, hip flexion reached 121.3°, but was greater in some individuals. The hip flexion range during kneeling was similar to that of ascending stair, which was 69.1° and 67.6°, respectively. The hip flexion was similar during jogging and walking, which was 42.1° and 39.2°, respectively. Hip extension only appeared in walking and jogging, and just −4.9° can satisfy the requirements of hip extension. The maximum adduction angle reached −7.3° during ascending stair. Kneeling and squatting just required hip abduction; the angles were large and reached 17.5° and 18.4°, respectively. The hip internal rotation was greater during descending stair, which reached −20.6°. The hip external rotation angle was greater during kneeling and squatting, which reached 20.6° and 17.6°, respectively. As an example, we used this motion simulation module to study whether commonly used THA has enough ROM to complete six ADLs. These THA design parameters and implant parameters were applied to the module. The module then used the integrated visualization and parameterized modeling functions to construct THA models. In the visual environment, the theoretical ROMs of these THA were obtained through the automatic impingement detecting function, as listed in Table 2.

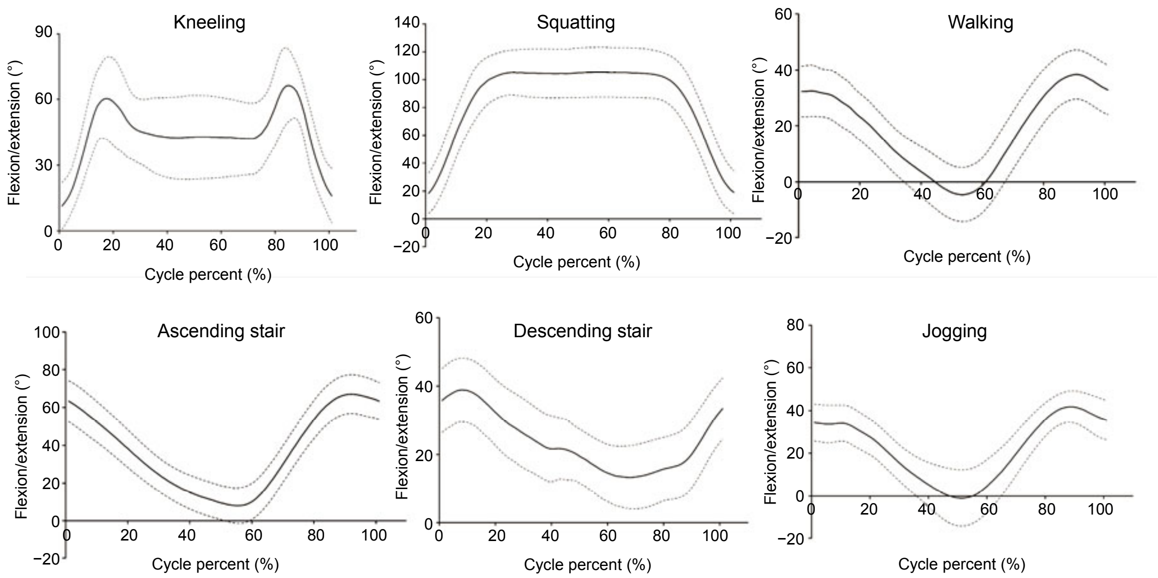

Fig. 1 Mean hip kinematic curves of healthy males in six ADLs
Data are expressed as mean±standard deviation (SD), *n*=15

Table 1 Maximum ROM of the hip in six ADLs

ADL	Flexion (°)	Extension (°)	Adduction (°)	Abduction (°)	Internal rotation (°)	External rotation (°)
Kneeling	69.1±14.4	11.6±10.7	1.2±5.3	17.5±5.0	−1.4±12.0	20.6±11.1
Squatting	121.3±17.3	17.2±14.5	1.3±4.9	18.4±5.4	−8.0±8.9	17.6±12.5
Ascending stair	67.6±10.0	7.7±9.4	−7.3±5.4	2.8±4.6	−12.5±11.6	−1.4±12.1
Descending stair	39.3±9.0	12.8±9.4	−6.6±4.3	4.7±5.5	−20.6±8.4	−10.4±7.6
Walking	39.2±8.1	−4.9±9.9	−7.3±6.5	6.4±6.5	−2.8±11.1	12.9±11.3
Jogging	42.1±7.5	−1.8±12.6	−6.3±6.4	7.0±6.2	−2.0±12.5	13.0±10.7

Data are expressed as mean±standard deviation (SD), *n*=15. The flexions of the hip and knee and the ankle dorsiflexion were positive; Hip, knee, and ankle abduction were positive; Hip, knee, and ankle external rotation were positive

The relationship between the cup/neck impingement and ADLs can be obtained through comparing the realistic hip kinematic data of general population with the theoretic ROM of THA. As is well known, joint motion is complicated in daily living because it requires a combination of flexion/extension, adduction/abduction, and internal/external rotation. Joint angle changes in three directions at the same time, so the motion risk of THA should be considered when three joint angles reach maximum values at the same time. If the average hip motion angle is larger than theoretical ROM of THA in either plane, it means that THA has impingement risk.

The experimental results accord well with the fact. The reliabilities of these kinematic data can be verified by comparison with previously published literature (Hemmerich *et al.*, 2006; Queen *et al.*, 2006; Protopapadaki *et al.*, 2007; Zhou *et al.*, 2012). The ROM of flexion/extension at the hip was much higher than the ROMs of adduction/abduction and internal/external rotation. Among six ADLS, the maximum flexion angle was 121.3° during squatting, while the maximum adduction/abduction and internal/external rotation angle did not exceed ±20.6° (Table 1). All these ADLs did not ask for much on the hip extension, the activity of maximum hip extension was walking, which only reached −4.9°.

According to the experimental results mentioned above, it seems that all maximum ROMs in the experimental activities (Table 1) were within the theoretical maximum ROM of this THA (Table 2). However, all these theoretical ROMs were measured from the normal standing position, and real impingement risk should be considered under the most dangerous position of ADL. The effect of hip extension for the cup/neck impingement or dislocation can be ignored because it is lower and only the impingement under the flexion condition should be considered. A typical THA (the values of general head-neck ratio (GR), stem-neck (CCD) angle, and stem abduction (SA) were fixed as 2.59, 135°, and 6°, respectively) is referred to in the following discussion. Through the motion simulation module, the theoretical ROMs of abduction/adduction and internal/external rotation of THA under the largest flexion condition of six ADLs were obtained, respectively, as shown in Table 3. Meanwhile, the actual joint angles under the largest flexion condition of six ADLs were listed.

The flexion ranges of walking and jogging were similar. The ROMs of adduction/abduction and internal/external rotation for these two activities were much smaller than the ranges offered by THA (Tables 1–3). Therefore, these two activities did not cause cup/neck impingement or dislocation. During ascending/

Table 2 Theoretical ROMs of the commonly used THA

THA's parameters GR, CCD, SA	Sagittal plane extension/flexion (°)	Frontal plane adduction/abduction (°)	Transversal plane internal/external rotation (°)
2.18, 135°, 6°	−55.2/118.8	−49.8/67.2	−130.8/63.0
2.59, 135°, 6°	−62.6/126.2	−54.8/72.2	−139.8/72.0
2.99, 135°, 6°	−67.8/131.6	−58.2/75.6	−146.6/78.8

THA's precision: 0.2°. The angles of femoral anteversion, acetabular anteversion, and acetabular inclination were defined as 15°, 20°, and 45°. There was only one motion in each plane (i.e., no combined motions)

Table 3 THA's theoretical ROMs of abduction/adduction and internal/external rotation as well as the actual joint angles under the largest flexion condition of six ADLs

ADL	Actual joint motion at maximum hip flexion (°)			Theoretic motion range of THA (°)	
	Flexion	Add/abduction	Inter/external rotation	Add/abduction	Inter/external rotation
Kneeling	69.1	15.7	18.6	−51.0/89.0	−66.4/106.6
Squatting	121.3	16.4	16.1	−5.6/129.2	−10.2/69.2
Ascending stair	67.6	−5.6	−8.3	−50.8/87.2	−66.6/109.8
Descending stair	39.3	−4.2	−16.7	−54.0/70.6	−65.6/143.4
Walking	39.2	−4.5	7.3	−54.0/70.6	−65.6/143.4
Jogging	42.1	−2.8	6.8	−59.6/78.2	−98.2/111.0

THA's precision: 0.2°. The values of GR, CCD and SA were fixed as 2.59, 135°, and 6°, respectively. The flexions of the hip and knee and the ankle dorsiflexion were positive; Hip, knee, and ankle abduction were positive; Hip, knee, and ankle external rotation were positive descending stair and kneeling, the ROMs of flexion were similar during kneeling and ascending stair, and their values were greater than that of descending stair. Likewise, the ROMs of adduction/abduction and internal/external rotation in these three activities did not exceed the theoretic ROM of THA (Tables 1–3). Clearly, cup/neck impingement or dislocation will not happen during ascending/descending stair and kneeling.

The squatting activity had the maximum flexion angle in the six ADLs; the mean maximum flexion angle was 121.3° (Table 1). In contrast, the theoretical flexion angle of THA was only 126.2° (Table 2). What is more serious is that the experimental result of 121.3° was only a statistical average, and some people may exceed this value. Out of a total of 90 squatting trials (6 trials×15 participants), participants exceed 126.2° of flexion 24 times. The adduction/abduction motion of squatting started from 1.3° to a maximum angle 18.4°; the abduction was 16.4° at the time of maximum hip flexion (Tables 1 and 3). The internal/external motion varied from −8.0° to a maximum angle of 17.6°; the external rotation reached 16.1° at the time of maximum hip flexion (Tables 1 and 3). At the same time, the THA's theoretical abduction range increased from 72.2° (standing position; Table 2) to 129.2° (maximum hip flexion position; Table 3), and external rotation range decreased from 72.0° (standing position; Table 2) to 69.2° (maximum hip flexion position; Table 3). Through comparing these motion angles, we know that these two motions should be secure. It is worth noting that the ranges of adduction and internal rotation are remarkably reduced except that the range of abduction increases significantly. The adduction angle of THA can only reach −5.6° at the time of maximum hip flexion and the theoretic internal rotation angle was merely −10.2° (Table 3). It is quite reasonable when this happened. Because the prosthetic neck was rotated to the rim of the cup when THA was at the maximum hip flexion, the neck was very easy to press against the cup's edge. So the patients underwent THA cannot randomly move their thighs in a squatting posture because of the low ROM limits of adduction and internal rotation. The above analyses show that the squatting activity probably induced the cup/neck impingement or dislocation, and thus executing a squat is very dangerous for patients who underwent THA.

It should be pointed out that the above analysis was based on a typical THA model. If a hip implant with smaller GR was used, then the theoretic ROM of THA will be significantly reduced and the impingement risk will be greater. Furthermore, the above analyses based on theoretic ROM did not take into account the effects of bony or soft tissue which, in fact, necessarily caused prosthetic impingement or dislocation to occur in advance. Therefore, in order to effectively eliminate the possibility of impingement, it is necessary to make the ROM of THA large enough before cup/neck impingement occurs. From the point of view of engineering, the most direct and effective way is to select the hip prosthesis with bigger head-neck ratio for patients subject to the specific individual circumstances or constraints. Furthermore, a positive surgical method can be a favorable procedure for avoiding adverse impact of bony or soft tissue. Therefore, the most efficient approach is to commit to see both sides grow together, so the postoperative function of the hip can get the best recovery.

Although THA has made great progress in joint disease, the THA still does not have high ROM. Some activities would be dangerous for patients who underwent hip joint replacement, such as squatting and sitting cross-legged. New hip implants and instrumentations that can provide higher ROM would be developed as soon as possible, and the patients' ability to attain ADLs still needs recovery.

Currently, some reported mathematical formula of THA and computerized models can complete these six motions from the neutral position (Seki *et al.*, 1998; D'Lima *et al.*, 2000; Widmer and Zurfluh, 2004; Widmer and Majewski, 2005; Padgett *et al.*, 2006; Ji *et al.*, 2010). It is remarkable that our module can not only simulate some basic motions recommended by some international organizations (AAOS, 1965; JOA, 1995), but it can also easily simulate any combined motion from any initial position based on demands. Besides, the motion simulation process in this module can be presented in real time, which is vivid for clinicians and users, and the visual function and the parameterized modeling increase the possibility of application in clinic (Ji *et al.*, 2010). It should be noted that there are two limitations for using this simulation module: (1) users must have an ADAMS/VIEW software license; (2) the neck cross-section should be round and the acetabular cup should be axisymmetric. Fortunately most commonly used hip prostheses fall into this category (Yoshimine, 2005; Ji *et al.*, 2010).

Prosthetic impingement of THA is one of the common serious orthopaedic postoperative complications and it directly causes the dislocation of THA. By taking our motion simulation module, the motion performance of THA could be obtained and the impingement and dislocation risks of THA could be analyzed. A practical instance tells us that THA has motion risk in the squatting activity. Thus, the study is essential for designing next-generation hip implants that can prevent poor ROM and perform all kinds of daily activities. Study of joint implants is still ongoing and people are looking forward to the development of new products that will benefit more and more patients. It is reasonable to believe that the motion simulation module of THA in the present study is helpful for clinical rehabilitation engineering and hip implant design and optimization.

Materials and methods

In this study, a motion simulation module of THA was used. It can simulate all rotation motions of implants and quantify the maximum rotation angle (Ji *et al.*, 2010). The realistic hip kinematic data of general population had been measured by using the optoelectronic 3D motion tracking system.

Detailed materials and methods are described in the supplementary materials Data S1.

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Compliance with ethics guidelines

Hai ZHOU, Cheng-tao WANG, Wen-ting JI, Xiang-sen ZENG, Shu FANG, and Dong-mei WANG declare that they have no conflict of interest.

All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2000(5). Informed consent was obtained from all patients for being included in the study.

References

AAOS (American Academy of Orthopaedic Surgeons), 1965. Joint Motion: Method of Measurement and Recording. American Academy of Orthopaedic Surgeons, Committee for the Study of Joint Motion, Chicago.

Brown, T.D., Callaghan, J.J., 2008. Impingement in total hip replacement: mechanisms and consequences. *Curr. Orthop.*, **22**(6):376-391. [doi:10.1016/j.cuor.2008.10.009]

D'Lima, D.D., Urquhart, A.G., Buehler, K.O., Walker, R.H., Colwell, C.W.Jr., 2000. The effect of the orientation of the acetabular and femoral components on the range of motion of the hip at different head-neck ratios. *J. Bone Joint Surg. Am.*, **82**(3):315-321.

Hemmerich, A., Brown, H., Smith, S., Marthandam, S.S., Wyss, U.P., 2006. Hip, knee, and ankle kinematics of high range of motion activities of daily living. *J. Orthop. Res.*, **24**(4):770-781. [doi:10.1002/jor.20114]

JOA (Japanese Orthopaedic Association), 1995. Range of Joint Motion and Method of Measurement. Japanese Orthopaedic Association, Committee of Joint Motion, Tokyo.

Ji, W.T., Tao, K., Wang, C.T., 2010. A three-dimensional parameterized and visually kinematic simulation module for the theoretical range of motion of total hip arthroplasty. *Clin. Biomech.*, **25**(5):427-432. [doi:10.1016/j.clinbiomech.2010.01.012]

Kessler, O., Patil, S., Wirth, S., Mayr, E., Colwell, C.W.Jr., D'Lima, D.D., 2008. Bony impingement affects range of motion after total hip arthroplasty: a subject-specific approach. *J. Orthop. Res.*, **26**(4):443-452. [doi:10.1002/jor.20541]

Padgett, D.E., Lipman, J., Robie, B., Nestor, B.J., 2006. Influence of total hip design on dislocation: a computer model and clinical analysis. *Clin. Orthop. Relat. Res.*, **447**:48-52. [doi:10.1097/01.blo.0000218748.30236.40]

Patel, A.B., Wagle, R.R., Usrey, M.M., Thompson, M.T., Incavo, S.J., Noble, P.C., 2010. Guidelines for implant placement to minimize impingement during activities of daily living after total hip arthroplasty. *J. Arthroplasty*, **25**(8):1275-1281. [doi:10.1016/j.arth.2009.10.007]

Protopapadaki, A., Drechsler, W.I., Cramp, M.C., Coutts, F.J., Scott, O.M., 2007. Hip, knee, ankle kinematics and kinetics during stair ascent and descent in healthy young individuals. *Clin. Biomech.*, **22**(2):203-210. [doi:10.1016/j.clinbiomech.2006.09.010]

Queen, R.M., Gross, M.T., Liu, H.Y., 2006. Repeatability of lower extremity kinetics and kinematics for standardized and self-selected running speeds. *Gait Posture*, **23**(3): 282-287. [doi:10.1016/j.gaitpost.2005.03.007]

Seki, M., Yuasa, N., Ohkuni, K., 1998. Analysis of optimal range of socket orientations in total hip arthroplasty with use of computer-aided design simulation. *J. Orthop. Res.*, **16**(4):513-517. [doi:10.1002/jor.1100160418]

Tanino, H., Ito, H., Harman, M.K., Matsuno, T., Hodge, W.A., Banks, S.A., 2008. An in vivo model for intraoperative assessment of impingement and dislocation in total hip arthroplasty. *J. Arthroplasty*, **23**(5):714-720. [doi:10.1016/j.arth.2007.07.004]

Widmer, K.H., Zurfluh, B., 2004. Compliant positioning of total hip components for optimal range of motion. *J. Orthop. Res.*, **22**(4):815-821. [doi:10.1016/j.orthres.2003.11.001]

Widmer, K.H., Majewski, M., 2005. The impact of the CCD-angle on range of motion and cup positioning in total hip arthroplasty. *Clin. Biomech.*, **20**(7):723-728. [doi:10.1016/j.clinbiomech.2005.04.003]

Yoshimine, F., 2005. The influence of the oscillation angle and the neck anteversion of the prosthesis on the cup safe-zone that fulfills the criteria for range of motion in total hip replacements. The required oscillation angle for an acceptable cup safe-zone. *J. Biomech.*, **38**(1):125-132. [doi:10.1016/j.jbiomech.2004.03.012]

Yoshimine, F., Ginbayashi, K., 2002. A mathematical formula to calculate the theoretical range of motion for total hip replacement. *J. Biomech.*, **35**(7):989-993. [doi:10.1016/S0021-9290(02)00040-4]

Zhou, H., Wang, D.M., Liu, T.R., Zeng, X.S., Wang, C.T., 2012. Kinematics of hip, knee, ankle of the young and elderly Chinese people during kneeling activity. *J. Zhejiang Univ.-Sci. B (Biomed. & Biotechnol.)*, **13**(10): 831-838. [doi:10.1631/jzus.B1100355]

List of electronic supplementary materials

Data S1 Materials and methods

Recommended paper related to this topic

Kinematics of hip, knee, ankle of the young and elderly Chinese people during kneeling activity

Authors: Hai ZHOU, Dong-mei WANG, Tao-ran LIU, Xiang-sen ZENG, Cheng-tao WANG

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Abstract: Objective: The purpose of this study was to measure the kinematics of the lower limbs of Chinese people during normal kneeling activity, as such data could be valuable in designing joint prosthesis and arthroplasty that meet the needs of Chinese citizens' daily activities. Methods: Thirty young and twenty elderly Chinese participants with no personal history of joint diseases were recruited, and matched by age (average age: 23.8 years for the young group, 60.8 years for the elderly group). Each participant performed six trials during which three-dimensional (3D) kinematics data were collected and the means of the 3D angles of the ankle, knee, and hip joints of two groups were calculated. Results: There were no obvious differences between the two groups in the knee and ankle joints. The mean range of knee flexion was 139.6° for the young group and 140.9° for the elderly group. The mean range of ankle flexion was 35.7° for the young group and 37.6° for the elderly group. The maximal eccentric flexion at the hip joint was 67.5° for the young group compared to 100.5° for the elderly group. Conclusions: The elderly uses more hip flexion angles than the young when assuming the kneeling posture. The ranges of motion obtained during kneeling activity are greater than the reported mean ranges of motion achieved following joint arthroplasty. The data could be valuable in establishing criteria for lower limb prosthetics and rehabilitation protocol for the Chinese population.