Age-related changes in kinematics of the knee joint during deep squat

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Abstract

Researchers frequently use the deep knee squat as a motor task in order to evaluate the kinematic performance after total knee arthroplasty. Many authors reported about the kinematics of a normal squatting motion, however, little is known on what the influence of aging is. Twenty-two healthy volunteers in various age groups (range 21–75 years) performed a deep knee squat activity while undergoing motion analysis using an optical tracking system. The influence of aging was evaluated with respect to kinematics of the trunk, hip, knee and ankle joints. Older subjects required significantly more time to perform a deep squat, especially during the descending phase. They also had more knee abduction and delayed peak knee flexion. Older subjects were slower in descend than ascend during the squat. Although older subjects had a trend towards less maximal flexion and less internal rotation of the knee compared to younger subjects, this difference was not significant. Older subjects also showed a trend towards more forward leaning of the trunk, resulting in increased hip flexion and anterior thoracic tilt.

This study confirmed that some aspects of squat kinematics vary significantly with age, and that the basic methodology employed here can successfully detect these age-related trends. Older subjects had more abduction of the knee joint, and this may indicate the load distribution of the medial and lateral condyles could be different amongst ages. Age-matched

control data are therefore required whenever the performance of an implant is evaluated during a deep knee squat.

Keywords

3D knee kinematics; Squat; Age-related changes

Introduction

Squat is a motor task that requires wide range of motion of the knee joint under loaded condition. Knee surgeons therefore use the deep knee squat frequently as a method to evaluate knee function and knee kinematics after surgery. The way on how the operated knee performs in comparison to what is known for the normal knee joint is frequently used to quantify the result and eventually improve the design or surgical technique of the knee prosthesis. Numerous studies performed in patients who had total knee arthroplasty (TKA) have shown abnormal kinematic patterns as compared to the normal human knee [1], [2], [3], [4], [5] and [6]. Based upon these studies, newer designs are being developed continuously in order to restore the kinematics of the normal knees in a better way than previous designs [7]. Obviously, it is therefore crucial to know accurately how normal knee kinematics occur as the reference. Several authors have reported on the kinematics of the knee during a deep knee squat [8], [9] and [10]. However, to our knowledge, the influence of aging has not been evaluated well before on full three dimensional analysis including axial and coronal planes. Previous studies have indeed always used young subject as a control group in their evaluation of the knee squat [11] and [12].

Nevertheless, it is well known that aging has an important effect on knee kinematics during normal gait, so it is logical to assume that this is also true for other activities such as a deep squat. Older adults are reported to tend to walk slower and with shorter strides when compared to younger subjects [13], [14], [15], [16] and [17]. This is generally considered compensatory to the loss of motor function that occurs with aging [18] and [19]. The way how a certain activity is performed is a reflection of how the subject attempts to maximize comfort and endurance, and represents the best compromise between parsimony in energy utilization and safety. Older adults walk differently than younger subjects in order to increase stability and avoid falls, or to reduce the energetic cost of mobility. Therefore it is commonly believed that when studying joint kinematics during walking, this should be in comparison to an age-matched control group to account for the variance with age [17].

Besides gait, squatting is the second most frequently studied motor task for evaluating knee function. The reason is that during squatting the patient performs an active and loaded deep flexion of both knees, which allows the surgeon to study the kinematics of the knee during almost full range of motion under active and loaded condition, with both eccentric and

concentric quadriceps contraction. Several authors have reported on the effect of osteoarthritis or ACL-deficiency on the kinematics during squatting [20], [21], [22] and [23]. In contrast to gait however, the effect of aging has not been thoroughly investigated for squatting.

In case differences would exist between older and younger subjects in how they perform a deep knee squat, age-matched control data would be required as the standard for adequate comparison and evaluation of certain interventions such as TKA. The present study therefore intends to quantify how squat kinematics vary with increasing age. To describe these effects as detailed as possible we investigated an exhaustive list of kinematic parameters. It was thereby hypothesized that older subjects would show reduced knee range of motion in the three anatomical planes.

Methods

Twenty-two volunteers without musculoskeletal pathology were recruited for the study and gave their informed consent to participate. The study was approved by the ethical commission of University Hospitals Leuven in Belgium. The study group consisted of 14 males and eight females, with a mean age of 46.2 years (SD 21.4, range 21–76), and an average body mass index of 23.4 (SD 4.6, range 17.7–30.8). No subjects reported any condition that could affect their functional performance, except for one subject who had been treated one year previously for a right Achilles tendon rupture. His gait patterns demonstrated no evident effects on his knee motions.

Kinematic analysis

Each subject underwent one motion analysis session by a well-trained physical therapist, using a 14-camera standard infrared tracking system, which determined the 3D trajectories of 55 passive retro-reflective spherical markers (14 mm diameter) fixed onto the skin over anatomical landmarks of the lower limbs and trunk (Plug-in-Gait [24] with Knee Alignment Device [25], Vicon, Oxford, UK). In each session, subjects were asked to perform three repeated trials of a deep squat. For each squat, they were instructed to squat down as deep as possible and rise back up. No support from the upper limbs was allowed, such as gripping the thighs with the hands. Other aspects of the squat, such as speed and posture, were at the subjects' discretion.

Data analysis

Dynamic three-dimensional joint kinematics were calculated with Euler angles, then time-normalized over a 0–100% squat cycle. Start and end times of the cycle were defined at instances of maximal knee extension, from standing position to standing position. The resulting data were analyzed with automated procedures (Matlab, Mathworks, Natick, MA, USA) in order to extract several descriptive parameters of the kinematic curves, including timing measures and extreme values. These parameters were chosen for analysis as they were hypothesized to possibly vary with age. Standard repeatability indices were calculated specifically for the knee kinematic curves. Repeatability relative to the range of motion was measured with the coefficient of multiple correlation (CMC), while absolute repeatability was measured in degrees with the root-mean-squared error (RMS) of the curves [26].

The parameters measured for each subject were: age, body mass, height, and body-mass index (BMI); CMC, RMS, maximum, minimum, and excursion values of the knee rotations in the three anatomical planes during the squat; abduction–adduction and internal–external rotation angles of the hip and ankle at the start of the squat; time to complete the squat cycle; and percent of the squat cycle (%cyc) at the instant of deepest flexion.

Statistical analysis

The correlations between age and each of these resulting motion parameters were calculated (Minitab, State College, PA, USA). Correlations were compared to the null hypothesis of zero correlation, with significance threshold set at $p < 0.05$.

Results

Subject characteristics are summarized in Table 1. No significant correlations were found for age versus height, weight, BMI, or kinematic consistency indices (Fig. 1) ($p > 0.10$), demonstrating an even distribution of subject characteristics across the age range. However, age showed significant positive correlations with squat time ($R = 0.636$, $p = 0.001$) and %cycle at maximum knee flexion ($R = 0.488$, $p = 0.021$) (Fig. 2). Squat time increased by 0.0581 s per year older, and %cycle at deepest flexion increased by 0.311% per year older. Significant negative correlations were found for age versus minimum ($R = -0.586$, $p = 0.004$) and maximum ($R = -0.559$, $p = 0.007$) abduction–adduction angles in the knee joint, with older subjects showing more abduction. Maximum and minimum abduction–adduction angles decreased by 0.167° and 0.276° per year older, respectively. All the remaining parameters were not significantly correlated with age (Table 2).

Table 1. Subject group characteristics.

Subjects	<i>n</i>	Men	Women		Mean	SD	Min	Max
All	22	14	8	Age	46.2	21.4	21.8	75.4
				BMI	23.4	4.6	17.7	30.8
Older (> 45 years)	12	7	5	Age	58.3	9.4	45.4	75.4
				BMI	24.6	3.5	17.7	30.8
Younger (< 45 years)	10	7	3	Age	31.7	9.8	21.8	44.3
				BMI	22.1	2.7	18.6	27.3

Characteristics of analyzed subjects, including two age groups: subjects older and younger than 45 years.

Repeatability indices of knee kinematics curves, versus subject age

Fig. 1. Four variables found to have significant non-zero correlations with subject age: squat time, %cycle at peak knee flexion, maximum ab/adduction, and minimum ab/adduction.

Fig. 2. Repeatability of the knee rotation curves versus subject age. Repeatability relative to the range of motion was measured by the coefficient of multiple correlation (CMC). Absolute repeatability, in degrees, was measured with the root-mean-square of the errors (RMS), which is similar to the average standard deviation of the curves across the entire cycle. Repeatability of knee rotations appeared unaffected by age.

Table 2. Overview of parameters analyzed.

Category	Parameter	Correlation with age	<i>p</i>
Subject parameters	Age	n/a	
	Body mass (kg)	0.156	0.489
	Height (cm)	− 0.270	0.225
Repeatability	Body-mass index	0.353	0.107
	CMC, knee flexion–extension	0.265	0.234
	CMC, knee abduction–adduction	0.059	0.801
	CMC, knee in-external rotation	− 0.068	0.764
	RMS (°), knee flexion–extension	− 0.371	0.089
	RMS (°), knee abduction–adduction	0.051	0.821
	RMS (°), knee in-external rotation	− 0.093	0.681
	Hip abduction–adduction at start (°)	− 0.098	0.665
	Hip in-external rotation at start (°)	− 0.095	0.674
	Ankle abduction–adduction at start (°)	0.234	0.294
	Ankle in-external rotation at start (°)	− 0.222	0.321
	Knee flexion–extension at start (°)	0.389	0.073
	Knee flexion–extension maximum (°)	− 0.245	0.273
	Knee flexion–extension excursion (°)	− 0.347	0.114
	Knee abduction–adduction at start (°)	− 0.436	0.042
Kinematics	Knee abduction–adduction maximum (°)	− 0.559	0.007
	Knee abduction–adduction minimum (°)	− 0.586	0.004
	Knee abduction–adduction excursion (°)	0.355	0.105
	Knee in-external rotation maximum (°)	− 0.263	0.237
	Knee in-external rotation minimum (°)	0.040	0.861
Timing	Knee in-external rotation excursion (°)	− 0.359	0.100
	Cycle time (s)	0.636	0.001
	%Cycle at deepest flexion (%)	0.488	0.021

Summary of parameters analyzed. Parameters found to have significant correlations with age are highlighted.

Further analysis revealed that the lack of significance of some parameters was mainly due to outlier data from one 21.9 year-old female subject. The subject took on a relatively wide squatting stance, with 15.7° starting hip abduction versus a subject average of 8.4°. This led to apparent squat difficulty and reduced range of knee flexion. When the data from this subject

were eliminated, additional significant correlations were detected between age and maximal flexion, and internal–external rotation of the knee joint. However, only the full set of original data is reported here, since only some of the data from this subject were outliers, and the subject was free to choose her own stance.

When the subjects were grouped in two age groups, there was no statistically significant difference between “younger” (< 45 years) and “older” (> 45 years) groups. However, a trend was observed that older subjects showed more thorax anterior tilt, more hip flexion, smaller and delayed maximal knee flexion, more knee abduction, less knee internal rotation, and less ankle dorsiflexion. Generally these patterns indicated more anterior leaning by older subjects.

Discussion

The aim of this study was to investigate the kinematics of a deep knee squat activity in healthy subjects with a wide variability in age, and to document the influence of age on how a deep knee squat is performed. This study confirmed that some aspects of the squat kinematics vary significantly with age, and that the basic methodology employed in our study can successfully detect these age-related trends.

The main finding in this study was that increased age was correlated with larger maximal knee abduction during the squat. To our knowledge, age-related difference in abduction–adduction kinematics during squat has not been evaluated before. The current study revealed that older subject had more valgus alignment during a squat maneuver. Abd-adduction alignment during movement can cause an imbalanced articular load distribution, and potential articular surface separation after TKA. Several authors have reported about articular surface separation, or ‘lift-off’ after TKA [27], [28] and [29], but age-related kinematic changes were never taken into account in its interpretation. The results of this study therefore suggest that age-matched kinematic analysis including the coronal plane would be needed in future clinical studies.

Many authors have reported on the influence of aging on normal gait [18] and [19], which is attributed by the fact that aging-related neuromuscular impairment is associated with a significant decline in muscle strength, secondary to a loss of muscle mass. This study demonstrated that older subjects needed longer time for performing a squat, especially in descending phase. Group comparison between ages showed a trend that older subjects also

showed more anterior inclination of the thorax and pelvis, more flexion in the hip joint, less flexion in the knee and ankle joint. Just as what has been demonstrated for gait, age-related muscular weakness may provide an explanation for these results.

With respect to the transverse plane, our data demonstrated that tibia rotated internally with increasing flexion during squat. This is in agreement with previous reports [11], [12], [30] and [31], but interesting to note was that older group showed a trend towards less internal rotation compared to younger subjects. This means that older subjects probably demonstrate less “roll back” movement of the lateral condyle. Multiple factors have an influence on femoral roll back, such as the status of the cruciate ligaments, collateral ligaments, and menisci. Several authors have reported age-related changes of these structures [32], which could be a possible explanation for our findings.

Despite the fact that we believe that the findings from our study are interesting and shed new light on the normal kinematics during a knee squat, our work has also some limitations. The sample size is relatively small leading to unequal gender distributions. Numerous studies have demonstrated that women have different motion patterns than men [33], [34], [35] and [36]. Further study with more subjects distinguishing female to male would therefore be needed. Some trends between older and younger subjects in group comparisons were seen, but not statistically significant in this study. Desloovere et al. reported that squat kinematics has only smaller repeatability than other activities such as normal walking or turning, because of the smaller constraints of the knee joint [37]. There is a possibility to detect some findings when larger number of the subjects was studied. Another limitation of this study is that stance widths while squatting were not uniform. The stance width would have an influence on the kinematics of all the joints. The results might have been different with a constant stance. However, we evaluated the natural way of the squatting activity like these subjects would have done in their daily lives.

Conclusion

In conclusion, our study has demonstrated that some aspects of squat kinematics vary significantly with age. We therefore believe that age-matched control data are required whenever the performance of an implant or surgical procedure is evaluated during a deep knee squat.

Conflict of interest

This study was sponsored by and conducted at the European Centre for Knee Research, a part of Smith & Nephew, Inc., which employs the authors and researcher P Wong and L Labey. The authors thank the staff and resources at Smith & Nephew.

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