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Gender differences in knee morphology and the prospects for implant design in total knee replacement

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ABSTRACT

Background: Morphological differences between female and male knees have been reported in the literature, which led to the development of so-called gender-specific implants. However, detailed morphological descriptions covering the entire joint are rare and little is known regarding whether gender differences are real sexual dimorphisms or can be explained by overall differences in size.

Methods: We comprehensively analysed knee morphology using 33 features of the femur and 21 features of the tibia to quantify knee shape. The landmark recognition and feature extraction based on three-dimensional surface data were fully automatically applied to 412 pathological (248 female and 164 male) knees undergoing total knee arthroplasty. Subsequently, an exploratory statistical analysis was performed and linear correlation analysis was used to investigate normalization factors and gender-specific differences.

Results: Statistically significant differences between genders were observed. These were pronounced for distance measurements and negligible for angular (relative) measurements. Female knees were significantly narrower at the same depth compared to male knees. The correlation analysis showed that linear correlations were higher for distance measurements defined in the same direction. After normalizing the distance features according to overall dimensions in the direction of their definition, gender-specific differences disappeared or were smaller than the related confidence intervals.

Conclusions: Implants should not be linearly scaled according to one dimension. Instead, features in medial/lateral and anterior/posterior directions should be normalized separately (non-isotropic scaling). However, large inter-individual variations of the features remain after normalization, suggesting that patient-specific design solutions are required for an improved implant design, regardless of gender.

1. Introduction

The implant design in total knee arthroplasty (TKA) is crucial for the functional restoration of the knee [1] and associated directly with the clinical outcome [2–5]. Modular implant systems are used conventionally with a limited number of size gradations so that the surgeon has to choose a best compromise [6]. Thereby, misfitting implants can lead to functional limitations, soft tissue

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irritations, bleeding, increased pressure and pain and, thus, decrease durability and patient satisfaction [2,7–9]. Chung et al. showed that standard knee designs cover Korean female femora dimensions only poorly, with negative clinical outcome [2]. Therefore, detailed knowledge about the characteristics of individual morphological features and its consideration is essential for improved endoprosthetic care.

The morphology of the knee joint has been widely studied in the last few decades and shape differences have been reported, for example, between ethnicity and gender. Most studies considered features of a single bone, mainly the femur, whereas few described the entire knee joint. The features can be categorized into "distance features", "angular features", and "features of curvature". The feature detection has been performed mostly using X-ray films, rulers, calipers, goniometers, templates or axial plane measurements on computed tomography (CT)/magnetic resonance imaging (MRI) data with inherent measurement errors and user dependencies. Recent studies have used an automated three-dimensional (3D) morphological analysis, potentially eliminating these errors [10].

Parsons, as early as 1913, investigated the characteristics of the femur and reported gender differences in overall size [11]. An extensive study by Mahfouz et al. demonstrated both gender and shape differences among Caucasian, African American and East Asian populations based on 11 femoral and nine tibial features considering the segmented 3D surface data of 1000 healthy knees [12]. The gender-specific differences motivated the introduction of gender-specific implants. The design modification addresses primarily the medial/lateral (ML) to anterior/posterior (AP) ratio and the anterior flange (patellar shield) of the femoral component. Previous studies reported significantly different ML/AP or AP/ML ratios in female and male [4,13–15]. By contrast, Fehring et al. found no gender-specific differences regarding the anterior condylar anatomy [16] and Voleti et al. reported no differences in the ratio of the posterior condylar offset to condylar height of the femur [17]. In conclusion, it is still controversially discussed whether gender-specific differences are actually sexual dimorphism (phenotypic difference between male and female) or due to overall differences in size and can potentially be equalized due to a scaling [18]. Recent clinical studies underline these findings by reporting no clinical benefit in short-term follow-up of gender-specific TKA compared to unisex solutions [19,20].

The literature presented illustrates that knee morphology has been extensively studied, however, with its own limitations. The femur, and less often the tibia, is the focus of investigations. The number of features is limited, as well as the number of cases, and measurement strategies can be partially deficient. Finally, gender-specific differences are insufficiently considered.

The aim of this study was a comprehensive exploratory analysis of the femur and tibia morphology under gender-specific aspects for a high number of cases for an improved knee reconstruction and implant design. This included the identification of morphological features and their standardized automatic detection for a reliable statistical analysis. It was specifically hypothesized that: (1) knee morphology shows a distinct sexual dimorphism; (2) a single feature is insufficient for adequate normalization; (3) gender-specific differences can be eliminated by a small number of features; and (4) inter-individual differences are greater than differences in gender after normalization.

2. Material and methods

2.1. Subjects

A dataset of 412 bone surfaces, 248 female (60.19%) and 164 male (39.81%), of the native distal femur and the proximal tibia were acquired by CT. The anonymized CT data originated from patients scheduled consecutively for TKA with usually advanced osteoarthritis. The knees were scanned using 1–1.5 × 0.5–0.625 mm (thickness × increment). The data were segmented semi-automatically to obtain osteophyte-free data and covered the region of approximately 10 cm above and below the knee joint gap. After segmentation, the surface data were exported to triangulated surface meshes for feature extraction with a constant edge length of one millimetre, which accurately reflected the morphology, while minimizing computational costs. Furthermore, the hip and ankle joint centres were recorded in the same coordinate system for later standardized definition of joint coordinate systems.

2.2. Features of the native knee

Morphological features were determined from the femur and tibia following the literature and our own considerations. The patella was not considered since it is often not replaced during TKA and plays a minor role in knee implant planning. We identified 34 features of the femur overall (Table 1). A dimensionless ML/AP aspect ratio was calculated based on the epicondylar width and overall anteroposterior length to further quantify the morphology.

Regarding the tibia, we determined 21 features to characterize the morphology (Table 2). Apart from the features described in literature, we introduced eight additional features, such as functional slopes and measurements in the frontal plane. The functional slopes distinguish from the conventional slopes considering the limiting points. The conventional slopes evaluate the inclination of the entire plateau, whereas the functional slopes are defined to consider only the articulating part. As in the case of the femur, a tibial ML/AP ratio was also calculated by dividing the mediolateral width by the anteroposterior height.

2.3. Feature detection

Fully automatic methods have been developed for the femur and tibia to determine the features in the given dataset, which have been partly presented [21,22]. These were implemented in MATLAB (The MathWorks, Inc., Natick, MA, USA).