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The knee adduction angle of the osteo-arthritic knee: A comparison of 3D supine, static and dynamic alignment

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ABSTRACT

Background: End-stage knee osteoarthritis (OA) commonly results in knee arthroplasty. Three dimensional (3D) supine imaging is often used for pre-operative planning to optimise post-operative knee adduction angles (KAA). However, supine imaging may not represent loaded knee alignment. The aim of this study was to investigate differences in knee alignment under supine, static and dynamic conditions in healthy subjects and subjects with knee OA.
Methods: Nine healthy subjects and 15 subjects with end-stage knee OA were recruited. All subjects underwent supine imaging and motion capture during gait. KAAs were calculated from supine images (SUPINE), upright standing (STATIC) and at the first peak ground reaction force during gait (DYNAMIC), and were compared.
Results: KAAs were significantly higher (more varus) during gait compared with static (loaded and unloaded) in healthy subjects ($p < 0.01$) but not in subjects with knee OA. There was a good correlation between SUPINE and DYNAMIC for both healthy and OA subjects ($R^2 > 0.58$), with differences in the two relationships; healthy knees had a higher KAA during gait for any given KAA in the supine position, whereas OA knees that were valgus in imaging became more valgus during gait, and the opposite occurred for varus knees.
Conclusions: Factors that may contribute to the noted differences between healthy and OA subjects include morphological changes in the joint as a result of OA, and gait compensation strategies in people with end-stage OA. Dynamic 3D motion capture provides important information about functional alignment that is not provided by supine imaging or static motion capture.
Clinical Relevance: Gait analysis may provide useful information to the surgeon during surgical planning of knee arthroplasties.

1. Introduction

Osteoarthritis the most common joint disorder in the UK and is a growing problem due to the aging population. The knee-joint is commonly affected and end-stage knee OA usually involves surgical interventions (total or unicompartmental knee arthroplasties). Such surgeries are growing in number, with their utilisation doubling between 1999 and 2008 [1].

Alignment at the knee joint has been related to disease progression in medial knee OA [2] due possibly to morphological changes in the pathological knee joint, such as cartilage wear [3], subchondral bone expansion [4] and meniscal pathology. High knee adduction moments have been reported in people with severe OA compared with a control group [5] and associated with knee malalignment and an increase in OA severity [5,6]. The post-operative knee adduction angle (KAA) is a key variable since malalignment has been shown to increase strain on implant surfaces [7] by influencing the mediolateral distribution of forces across the femorotibial joint [8], ultimately leading to implant loosening and failure [9] and the need for revision surgeries. Pre-operative planning aims to correct this knee joint malalignment (varus–valgus) [10] to ensure optimal post-operative outcomes.

Three dimensional (3D) imaging (Computed Tomography and Magnetic Resonance Imaging) is therefore often used for more accurate pre-operative planning. 3D supine imaging of unloaded knees may however not be representative of their alignment during static or dynamic loading, leading to over or under estimation of optimal knee alignment. Thus 3D motion capture, to predict lower limb alignment during loaded and dynamic tasks, has been proposed as a useful addition to pre-operative planning. Quantification of the magnitude of the difference between statically unloaded and loaded joints and dynamically loaded joints would therefore be useful to inform pre-operative planning; this would allow a plan to be developed based on known differences between static and dynamic alignment. However, joint deterioration due to knee OA may affect the dynamically loaded joint in an unpredictable manner. In addition, muscle loading and ligament laxities contribute to

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determine the position of the knee joint during dynamic tasks, which we believe can affect dynamic relative to static loading differently between individuals. Thus patient-specific gait analysis may be important to improve outcomes. Rather than correcting for the static malalignment alone, and assuming that the dynamic situation is similar across patients, as currently used in pre-surgical planning, this would allow the surgeon to correct for both static and dynamic malalignment.

This has previously been trialled in the surgical management of ambulatory cerebral palsy [11] and spastic equinovarus deformity of the ankle [12] with some success. In these conditions, surgical interventions attempt to correct joint deformities and reduce muscle stiffness by lengthening, releasing or transferring tendon attachments. The incorporation of gait analysis in these conditions has been shown to alter surgical planning decisions [11,12], resulting in improved agreement between surgeons [12], and to reinforce decision making in surgical planning [11]. Planning for knee arthroplasty similarly attempts to correct joint deformities, primarily in the frontal plane, thus the incorporation of pre-operative gait analysis may similarly influence surgical decision making.

Previous studies have compared radiographic measures of alignment to dynamic gait analysis to evaluate its use in the diagnosis and management of lower limb pathology [13,14]. However these studies used weight bearing two dimensional images, which do not have the required accuracy and sensitivity for pre-operative planning due to uncertainties in orientation and distortion [15,16]. Lastly, comparisons with healthy subjects are omitted due to ethical concerns over radiation exposure which precludes an analysis of pathological changes in gait patterns.

Based on the growing use of unloaded 3D imaging in surgical technologies, the aims of this study were:

1. To quantify the magnitude of change in knee adduction angles measured from 3D unloaded supine imaging to those from 3D motion capture during upright standing and dynamically loaded gait in healthy and OA knees.
2. To understand whether the relationship between knee adduction angles measured from 3D unloaded images and those from 3D motion capture during gait differs between subjects with and without knee OA.

It is important to understand whether the relationship and/or magnitude of change differs between healthy and OA subjects, in order to justify the incorporation of patient-specific gait analysis into surgical planning. We hypothesised that knee adduction angles measured from gait analysis would be greater than those measured during both supine imaging and upright standing, and that the magnitude of change would be greater in OA compared with healthy subjects, due to differences in joint morphology.

2. Methodology

Fifteen subjects clinically diagnosed with knee OA and scheduled for unilateral or total knee arthroplasty (13 male and 2 female), and 9 healthy subjects (5 male and 4 female) were recruited. Subjects were excluded if they had rheumatoid arthritis or any other systemic inflammatory condition, a Body Mass Index (BMI) > 35 kg/m^2 or any neurological or musculoskeletal condition involving the lower limbs. This study had ethical approval from the South West London Research Ethics Committee and the Joint Research Office at Imperial College NHS Trust, and all subjects provided written informed consent. All subjects underwent 3D motion capture, and healthy and OA subjects underwent Magnetic Resonance Imaging (MRI) scans and pre-operative Computed Tomography (CT) scans, respectively.

A Vicon motion tracking system (Vicon Motion Systems, Oxford, UK) comprising 10 cameras was used to track 20 reflective markers positioned on the subject's pelvis and lower limbs in addition to four marker clusters positioned on the subject's left and right thigh and calf, as described previously [17]. One investigator positioned markers for all trials. Two force plates (Kistler Instruments AG, Winterthur, Switzerland) were embedded in a 6 m walkway. Each subject completed one static upright standing trial and three walking trials at a self-selected speed. 3D marker positions and ground reaction forces were sampled synchronously at 100 and 1000 Hz respectively.

2.1. Data analysis

2.1.1. Imaging

MRI and CT data was converted into 3D models using Mimics and analysed using 3-matic software suite (Materialise IV, Belgium). The Hip Joint Centre (HJC) was located using the centre of a sphere fit to the femoral head articulating area. The femoral anatomical frame was created using the femoral epicondyles and HJC and centred at the midpoint between the femoral epicondyles. The tibial anatomical frame was created using the femoral epicondyles and midpoint of the malleoli at the ankle and centred at the midpoint of the femoral epicondyles, as suggested previously [18]. KAAs were computed by measuring the angle between the femoral and tibial anatomical frames in the frontal plane using Matlab (The MathWorks Inc., Natick, MA), referred to as SUPINE in this study. Positive and negative angles represent adduction and abduction respectively.

2.1.2. Motion capture

Joint angles were calculated using custom written code in body builder software, as described and validated previously [17]. Briefly, the position of the HJC was estimated using an equation reviewed by Horsman et al. [19]. The knee and ankle centres were located using the midpoint of the femoral epicondyles and ankle malleoli respectively, similar to that performed on imaging datasets. All gait data was time normalised to the gait cycle. The average KAA from the static standing trial (STATIC) and the KAA at the first peak of the vertical ground reaction force (GRF) from the second of three walking trials (DYNAMIC) were extracted for each subject. This was done for consistency; an average was not used since we did not have three SUPINE trials from which to calculate an average. For OA subjects, the affected data was extracted for the affected side, and for control subjects data for one randomly selected side was extracted.

All comparisons were tested for equality of variances (F test) and normality (Shapiro Wilks test). Differences in age and body mass index (BMI) between the two groups were assessed using *t*-tests. Differences in gender distribution between the two groups were assessed using Fisher's Exact test. The effect of statistically significant differences in demographics (age and BMI) on KAAs (SUPINE, STATIC and DYNAMIC) was assessed using multiple linear regression analysis.

KAAs were compared between measurement methods using paired *t*-tests, and between group (Healthy vs OA), using independent sample *t*-tests. Relationships between change in KAA (DYNAMIC–SUPINE) and walking speed, and KAAs from SUPINE and DYNAMIC were analysed using linear regression. For all statistical tests $p < 0.05$ was considered significant. All statistical analyses were performed in IBM SPSS Statistics 20 (IBM Corp., Armonk, NY). Results are presented as mean (SD).

3. Results

Subjects with knee OA were significantly older (54 (27–71) years vs. 31 (22–42) years; $p = 0.00$) and had a higher BMI (25.7 (21.3–33.8) kg/m^2 vs. 22.2 (18.9–25.3) kg/m^2; $p = 0.01$) than healthy subjects. However no significant confounding effect was observed on SUPINE, STATIC or DYNAMIC imaging due to age and BMI discrepancies assessed using multiple linear regression ($p > 0.05$). The difference in the gender distribution of groups did not reach significance (OA = 13 male and 2 female vs. Healthy = 5 male and 4 female, $p > 0.05$). OA subjects walked significantly more slowly than healthy subjects (1.01 (0.18) vs 1.22 (0.09) m/s, respectively). Change in KAA from SUPINE to DYNAMIC did not correlate with walking speed in OA subjects ($R^2 = 0.04$), and had only a low correlation in healthy subjects ($R^2 = 0.32$).

Overall, KAAs measured when SUPINE were significantly higher compared with STATIC ($p = 0.01$) and lower compared with DYNAMIC ($p = 0.01$) measurements (Table 1 and Fig. 1). There was no significant difference between the mean KAAs of healthy and OA subjects; however, the range of data from OA subjects was greater than healthy subjects for all measurement methods (Fig. 2). Within the healthy group, KAAs measured