Hip-Knee-Ankle (HKA) angle modification during gait in healthy subjects

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\textbf{ABSTRACT}

\textbf{Background:} Achieving a neutral static Hip-Knee-Ankle angle (sHKA) measured on radiographs has been considered a factor of success for total knee arthroplasty (TKA). However, recent studies have shown that sHKA seems to have no effect on TKA survivorship. sHKA is not representative of the dynamic loading occurring during gait, unlike the dynamic HKA (dHKA).

\textbf{Research question:} The primary objective was to see if the sHKA is predictive of the dynamic HKA (dHKA). A secondary objective was to document to what degree the dHKA changes during gait.

\textbf{Methods:} We analysed 3D knee kinematics during gait of a cohort of 90 healthy individuals with the KneeKG\textsuperscript{™} system. dHKA was calculated and compared with sHKA. Knees were considered “Stable” if the dHKA remained in valgus or varus for greater than 95% of the corresponding phase, and “Changer” otherwise. Patient characteristics of the Stable and Changer knees were compared to find associated factors.

\textbf{Results:} Absolute variation of dHKA during gait was 10.9 ± 5.3° for the whole cohort. The variation was less for the varus knees (10.3 ± 4.8°), than for the valgus knees (12.8 ± 6.1°, \(p = 0.008\)). We found low to moderate correlations (\(r = 0.266\) to 0.553, \(p < 0.001\)) between sHKA and dHKA values for varus knees and no significant correlation for valgus knees. Twenty percent (36/165) of the knees were considered Changers. The proportion of knees that were Changers was 15% of the varus versus 39% of the valgus (\(p < 0.001\)).

\textbf{Significance:} Lower limb radiographic measures of coronal alignment have limited value for predicting dynamic measures of alignment during gait.

1. Introduction

Hip-Knee-Ankle angle (HKA) measured on standing full-length radiographs is a common evaluation method to assess lower limb anatomy, diagnose pathologies, as a surgical planning tool and to assess success of the surgical procedure. A neutral coronal HKA has been the key alignment goal for total knee arthroplasty (TKA) for many years. It was believed to improve TKA survivorship and polyethylene wear. However, several long-term studies have recently failed to find a significant relationship between HKA and TKA survivorship [1–4]. These results could be explained by the fact that static HKA (sHKA) may be of limited value in estimating the dynamic loading that occurs during gait.

Dynamic measures have thus been gaining popularity in recent years. It has been shown that the healthy knee adduction angle through stance is correlated with the dynamic load on the medial compartment of the knee [5–7], with a greater angle resulting in a larger adduction moment and increased load. Increased knee adduction moments have also been reported in patients with osteoarthritis (OA) compared to healthy controls [8–10], while increased dynamic loading of the knee joint has been associated with the disease progression [11]. Finally, a larger knee adductor moment has been associated with early loosening of TKA prostheses [12,13].

Dynamic angular measurements of the knee seem to be a key factor of the progression of knee OA and the survivorship of TKA. The concept of the dynamic HKA (dHKA), which measures the coronal alignment of the knee throughout the gait cycle, has thus been considered as an alternative measure to the static sHKA. The dHKA may more accurately reflect the loading that occurs in the knee, and therefore be more predictive of long-term outcomes. To our knowledge, only one study [14] compared the sHKA with the dHKA during gait, in a healthy population. Duffell et al. recruited nine healthy participants, and found the dHKA to be in significantly greater varus during gait (by a mean of...
The goal of the present study was to analyse dHKA throughout the gait cycle on a healthy population and compare it with sHKA. The primary aim of the study was to see if the sHKA is predictive of the dHKA, and the secondary aim was to document to what degree the dHKA changes throughout gait. We hypothesised that the sHKA value has limited value for predicting dHKA, and that the dHKA can vary considerably during gait.

2. Material and methods

Ethical approval was obtained from the hospital research and ethics committee, and all participants gave informed consent. The subjects came from our recent study [15] analysing the knee kinematics of a cohort of 90 healthy individuals (49 females and 41 males). The subjects had to be 18 to 65 years old and were excluded if they had any lower limb pathologies, musculoskeletal disorder, or previous lower limb surgery. Each subject had a full-length weight-bearing (FLWB) radiograph to confirm the absence of knee joint degeneration. All demographic and radiographic data are presented in Table 1.

The 3D knee kinematic analyses were performed during gait with the KneeKG™ (Emovi Inc., Montréal, QC, Canada), which is a valid and reliable tool for measuring the knee joint movements [16–21]. After the installation of the KneeKG™ on the subjects and the calibration procedure [17,18], subjects were asked to walk on a treadmill to determine their self-selected walking speed (had to be > 2 km/h) [22]. All kinematic data were collected by one trained technician. A complete description of the methodology can be found in our previous study [15].

2.1. Kinematics data processing

3D kinematic analyses of 165 knees (75 subjects had bilateral evaluations, and 15 subjects had unilateral evaluation). Kinematic data were used to generate knee angles with the Knee3D™ software (Emovi Inc.): knee flexion-extension, abduction-adduction, and internal-external rotation, representing the motion of the tibia relative to the femur [23]. Mean knee angles were computed by averaging the 15 most repeatable gait cycles in each subject [24]. The knee angle curves were normalized from 1 to 100% of the average gait cycle. dHKA was calculated by projecting the hip, knee and ankle joint centers into the subjects’ frontal plane, and by measuring the angle formed by the vectors connecting the knee center to the hip and ankle centers (Fig. 1-A). The joint centers were estimated during the functional calibration procedure of the KneeKG™: [17,18] the hip joint center was defined during a lower limb circumduction movement; the knee joint center was defined as the projection of the femoral epicondyle’s midpoint on the functional knee flexion-extension axis and the ankle joint center

3.5°) compared to the sHKA.

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Table 1
Mean demographic and radiographic data: comparison between men and women.

<table>
<thead>
<tr>
<th></th>
<th>Entire cohort (n = 90 subjects, n = 165 knees)</th>
<th>Women (n = 49 subjects, n = 90 knees)</th>
<th>Men (n = 41 subjects, n = 75 knees)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>34.8 (min 20.0, max 64.0, SD 12.3)</td>
<td>34.8 (min 20.0, max 63.0, SD 12.7)</td>
<td>34.8 (min 21.0, max 64.0, SD 12.1)</td>
<td>0.997</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.69 (min 1.42, max 1.91, SD 0.11)</td>
<td>1.62 (min 1.42, max 1.78, SD 0.08)</td>
<td>1.78 (min 1.62, max 1.91, SD 0.06)</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>71.8 (min 36.0, max 118.0, SD 17.3)</td>
<td>62.5 (min 36.0, max 111.0, SD 14.4)</td>
<td>83.0 (min 63.0, max 118.0, SD 13.5)</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>24.8 (min 17.1, max 40.8, SD 4.6)</td>
<td>23.7 (min 17.1, max 40.8, SD 4.7)</td>
<td>26.1 (min 19.4, max 36.9, SD 4.1)</td>
<td>0.012</td>
</tr>
<tr>
<td>Walking speed (m/s)</td>
<td>0.76 (min 0.56, max 1.08, SD 0.11)</td>
<td>0.75 (min 0.56, max 1.03, SD 0.12)</td>
<td>0.78 (min 0.56, max 1.08, SD 0.11)</td>
<td>0.299</td>
</tr>
<tr>
<td>mLDFA (°)</td>
<td>88.3 (min 82.2, max 93.6, SD 2.3)</td>
<td>88.5 (min 82.3, max 93.4, SD 2.3)</td>
<td>88.1 (min 82.2, max 93.6, SD 2.4)</td>
<td>0.252</td>
</tr>
<tr>
<td>aLDFA (°)</td>
<td>82.6 (min 76.3, max 88.1, SD 2.2)</td>
<td>82.7 (min 77.5, max 87.8, SD 2.2)</td>
<td>82.4 (min 76.3, max 88.1, SD 2.3)</td>
<td>0.360</td>
</tr>
<tr>
<td>MPTA (°)</td>
<td>87.5 (min 80.2, max 92.2, SD 2.4)</td>
<td>88.4 (min 83.6, max 92.2, SD 1.7)</td>
<td>86.4 (min 80.2, max 91.5, SD 2.6)</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>sHKA (°)</td>
<td>-1.6 (min -9.4, max 7.3, SD 3.0)</td>
<td>-0.8 (min -7.4, max 7.3, SD 2.6)</td>
<td>-2.6 (min -9.4, max 5.0, SD 3.1)</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>

mLDFA = mechanical lateral distal femoral angle.

aLDFA = anatomical lateral distal femoral angle.

MPTA = mechanical medial proximal tibial angle.

sHKA = static hip-knee-ankle angle.

* n = 89.

** n = 40.
Table 2
Comparison of Stable and Changer knees X-ray angles and dHKA values during a mean gait cycle.

<table>
<thead>
<tr>
<th>Stable vs. changer knees</th>
<th>BMI (kg/m²)</th>
<th>sHKA (°)</th>
<th>mL DFA (°)</th>
<th>aL DFA (°)</th>
<th>MPTA (°)</th>
<th>dHKA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Variation phrase (°)</td>
<td>Max stance phase (°)</td>
<td>Mean stance phase (°)</td>
<td>Mean initial contact / loading response (°)</td>
<td>Mean mid-stance (°)</td>
</tr>
<tr>
<td>Whole cohort N=129</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>vs. 36 N=36</td>
<td>24.4 ± 4.2</td>
<td>−2.0 ± 3.0</td>
<td>88.5 ± 2.3</td>
<td>82.7 ± 2.2</td>
<td>87.1 ± 2.4</td>
<td>3.7 ± 1.6</td>
</tr>
<tr>
<td>Changers N=36 s</td>
<td>25.3 ± 4.6</td>
<td>−0.2 ± 2.5</td>
<td>87.7 ± 2.4</td>
<td>81.9 ± 2.1</td>
<td>88.7 ± 1.9</td>
<td>4.6 ± 2.3</td>
</tr>
<tr>
<td></td>
<td>0.271</td>
<td>0.001</td>
<td>0.079</td>
<td>0.062</td>
<td>0.000</td>
<td>0.009</td>
</tr>
<tr>
<td>Stables N=99 s</td>
<td>24.6 ± 4.3</td>
<td>−3.1 ± 2.2</td>
<td>88.9 ± 2.2</td>
<td>83.1 ± 2.1</td>
<td>86.7 ± 2.3</td>
<td>3.6 ± 1.6</td>
</tr>
<tr>
<td>vs. vs. 17 N=99</td>
<td>25.4 ± 3.0</td>
<td>−2.2 ± 1.9</td>
<td>89.3 ± 1.4</td>
<td>83.1 ± 1.7</td>
<td>88.6 ± 1.8</td>
<td>4.4 ± 1.5</td>
</tr>
<tr>
<td>Changers N=17 s</td>
<td>25.4 ± 3.0</td>
<td>−2.2 ± 1.9</td>
<td>89.3 ± 1.4</td>
<td>83.1 ± 1.7</td>
<td>88.6 ± 1.8</td>
<td>4.4 ± 1.5</td>
</tr>
<tr>
<td></td>
<td>0.508</td>
<td>0.105</td>
<td>0.499</td>
<td>0.846</td>
<td>0.002</td>
<td>0.062</td>
</tr>
<tr>
<td>sVarus N=19</td>
<td>24.1 ± 3.9</td>
<td>1.9 ± 1.8</td>
<td>87.0 ± 2.1</td>
<td>81.2 ± 2.0</td>
<td>84.4 ± 2.1</td>
<td>3.9 ± 1.9</td>
</tr>
<tr>
<td>vs. 28 N=18</td>
<td>25.2 ± 5.9</td>
<td>1.7 ± 1.2</td>
<td>86.2 ± 2.2</td>
<td>80.7 ± 1.8</td>
<td>88.8 ± 2.0</td>
<td>4.8 ± 3.0</td>
</tr>
<tr>
<td>Changers N=18 s</td>
<td>25.2 ± 5.9</td>
<td>1.7 ± 1.2</td>
<td>86.2 ± 2.2</td>
<td>80.7 ± 1.8</td>
<td>88.8 ± 2.0</td>
<td>4.8 ± 3.0</td>
</tr>
<tr>
<td></td>
<td>0.451</td>
<td>0.702</td>
<td>0.184</td>
<td>0.476</td>
<td>0.574</td>
<td>0.212</td>
</tr>
</tbody>
</table>

BMI = Body mass index.
sHKA = static hip-knee-ankle angle.
dHKA = dynamic hip-knee-ankle angle.
sVarus = static varus knee.
sValgus = static valgus knee.
mL DFA = mechanical lateral distal femoral angle.
anL DFA = anatomical lateral distal femoral angle.
MPTA = mechanical medial proximal tibial angle.
was defined as the midpoint of the malleoli. Mean changes in the dHKA during walking were also determined by averaging the 15 most repeatable gait cycles (Fig. 1B). Maximum and mean dHKA for the gait cycle, stance and swing phases, as well as mean dHKA for initial contact/loading response, mid-stance, terminal stance, and pre-swing phases were calculated. Knees were considered “Stable” if the dHKA remained positive or negative – i.e. in valgus or varus – for greater than 95% of the corresponding phase and were considered “Changer” otherwise.

2.2. Radiographic data collection

On FLWB X-rays: mechanical and anatomical lateral distal femoral angle (mLDFA and aLDFA), mechanical medial proximal tibial angle (MPTA), and static hip-knee-ankle angle (sHKA) were measured by one investigator with Impax software (Agfa Healthcare, Mortsel, Belgium) [15,25].

Table 3 shows the Pearson correlation coefficients between sHKA and dHKA values for the whole cohort, the sVarus/sValgus knees group, and Stable/Changer knees group.

3. Results

Among the 165 knees analysed in the present study, 116 (70%) were in sVarus (sHKA < 0), 46 (28%) in sValgus (sHKA > 0) and 3 (2%) in static neutral (sHKA = 0). dHKA absolute variation was 10.9 ± 5.3° [2.4° – 28.3°] for the whole cohort and less for the sVarus knees (10.3 ± 4.8° [2.4° – 26.3°]), than for the sValgus knees (12.8 ± 6.1° [2.9° – 28.3°], p = 0.008). Larger variations were present during the swing phase: 9.7 ± 4.9° [1.4° – 25.5°] for the whole cohort; 9.3 ± 4.7° [1.4° – 24.8°] for the sVarus knees and; 11.1 ± 5.4° [2.2° – 25.5°] for the sValgus knees (more than sVarus knees, p = 0.032). dHKA absolute variations during the stance phase were: 3.9 ± 1.8° [0.9° – 16.0°] for the whole cohort; 3.7 ± 1.6° [0.9° – 10.3°] for the sVarus knees and; 4.2 ± 2.4° [1.4° – 6.0°] for the sValgus knees (p = 0.144). Comparisons between Stable and Changer knees, and correlations between sHKA and dHKA, were then computed for the stance phase.

Table 3 shows the Pearson correlation coefficients between sHKA and dHKA values for the whole cohort, the sVarus/sValgus knees group, and Stable/Changer knees group.
dHKA values for the sValgus knees (Fig. 2-B) and the Changer knees groups.

3.2. Comparison between stable and changer knees

When comparing Stable and Changer knees, significant differences were found for sHKA (-2.0° vs. -0.2°, p = 0.001), MPTA (87.1° vs. 88.7°, p < 0.001), amplitude of dHKA (3.7° vs. 4.6°, p = 0.009), and all other dHKA values (p < 0.005) (Table 2). For the knees in sVarus, Stable knees had smaller MPTA (86.7° vs. 88.6°, p = 0.002) and smaller dHKA values (p < 0.005) than Changer knees. Conversely, no significant differences were found between Stable and Changer knees in sValgus. Comparing men and women results (Table 4), all dHKA values were significantly smaller in men than in women (p < 0.001), except for the absolute variation during the stance phase.

4. Discussion

The coronal alignment of the knee measured on a FLWB radiograph (sHKA) is still one of the key measures for clinicians performing a mechanically aligned TKA. However, the usefulness of this measure in predicting implant survivorship has been questioned. This may be explained by the poor correlation between the sHKA and the dynamic coronal alignment of the knee (dHKA) during gait, which has proven to be a good indicator of the dynamic load in the knee. On the other hand, the kinematically aligned TKA aims at restoring dHKA throughout gait cycle, but a clear description of normal dHKA on a large healthy cohort is still lacking. The main objective of the present study was to describe the dHKA of healthy subjects and see if it is correlated with sHKA. We found only one other study comparing sHKA with dHKA in a cohort of healthy knees. Duffell et al. looked at 9 healthy participants and reported a significant change (p < 0.01) from a mean sHKA of 0.5° valgus (SD 2.8) to a mean dHKA of 4.4° varus (SD 3.0). [14] Again the greatest change was seen in the valgus knees, that went from a mean of 2.0° valgus (SD 1.2) statically to a mean of 3.8° varus (SD 1.9, p < 0.01) during gait. This study used motion capture tracking system to calculate both the dHKA and the sHKA, but no radiographs were taken.

In TKA knees, Rivièere et al. in a cohort of 35 patients, using motion-capture gait analysis, found no significant correlation between the sHKA and the dHKA during stance phase (r = 0.14, p = 0.45) [27]. They found sHKA to have a moderate correlation with the mean and peak adduction moments (r = 0.31 and r = −0.352 respectively). Similarly, Orishimo et al. performing gait analysis on a cohort of 15 patients before and after TKA surgery, did not find any correlation between standing or dynamic coronal alignment of TKAs with peak adduction moments [28]. Moreover, improvement in the sHKA to neutral post-surgery did not correlate with a change in the peak adduction moments during gait. Miller et al. looked at the plateau load distributions in 15 patients post-TKA. The TKAs were neutrally aligned on post-operative radiographs and produced balanced loading between the tibial plateaus in the standing position [29]. However, less than half of the knees (40% at 2 years) achieved equal plateau load distributions in dynamic loading. In fact, both pre-operatively and post-operatively the dynamic load was independent of the sHKA.

It thus appear that sHKA poorly reflects dHKA, and therefore knee loading. That may explain why the sHKA, which is used to perform mechanically aligned TKA, has shown to be of poor value to predict implant survivorship [1–4]. As an alternative of mechanical alignment, kinematic alignment is a new technique for TKA to restore native femoro-tibial joint line orientation and laxity throughout knee range of motion [30]. However, precise indications for kinematically aligned TKA remain to be defined. There is currently a trend to not reproduce severe frontal constitutional deformity for fear of overloading the TKA, and therefore increase risk of failure. The description of a normal range of dHKA in a healthy population may help to define the limits of a kinematic aligned TKA.

There are no doubt other factors apart from coronal prosthetic alignment that affect how the knee will be loaded dynamically. A study looked at the joint line orientation in both healthy and osteoarthritic subjects [31]. It demonstrated that despite a range of sHKA alignments, the joint line remained parallel to the ground when standing in the healthy subjects. Conversely, in the subjects with OA, the joint line tended to slope down medially. Interestingly, studies of kinematic alignment for TKA have also demonstrated that the post-operative joint
line tends to be parallel to the ground, whereas it tends to slope down laterally in mechanically aligned TKAs [32,33]. The resultant functional joint line orientation may well be favourable for the overall load profile of a prosthetic joint.

Our study has some limitations. Soft tissue artefact may be an issue with traditional skin markers in gait studies. The KneegK system was developed to overcome this with the use of its harness and exoskeleton attachment system. The accuracy and reproducibility have been assessed, with a mean accuracy of 0.4° to 0.8° for measured angles [18,20]. On the other hand, the exoskeleton may not fit on all patients. Some patients have been excluded based on their extreme anatomy (morbidity obese, very short/tall person, etc.). Collected data are also limited to only one aspect of patient gait (walking at a comfortable speed 2–4 km/h). We cannot extrapolate the dHKA during running or jumping for example. It is important to note that the dHKA is not always well-defined in gait studies. Many studies simply measure the abduction/adduction angle between the tibia and the femur in a 3-dimensional frontal plane. In our method, dHKA was calculated in the 2-dimensional frontal plane, allowing appropriate comparison with radiographs.

5. Conclusions

This study involving healthy subjects showed that there was only a mild to moderate correlation between shKA and the dHKA for varus knees, and no correlation between the shKA and dHKA for valgus knees. Furthermore, a number of the knees demonstrated a switch in knees, and no correlation between the sHKA and dHKA for valgus knees. Correlation of coronal alignment have limited value for predicting dynamic measures of alignment during gait in a healthy population.

Conflicts of interest

The authors, their immediate families and any research foundations with which they are affiliated have not received any financial payments or other benefits from any commercial entity related to the subject of this article.

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References


