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Automated analysis of morpho-functional interbone parameters of the knee based on three-dimensional (3D) surface data

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Abstract

Interbone parameters of the knee are of relevance in clinical practice, e.g. for the assessment of the functional anatomy of the individual patient. However, respective landmark identification and parameter derivation is mostly done manually. An automated analysis could enable the processing of large datasets, which could again enable the derivation of reference ranges or safe zones for various populations. Hence, the aim of this study was to automate the derivation of interbone parameters from 3D surface data of the knee and to evaluate the method's robustness against a large dataset.

A dataset of 414 knees from patients scheduled for total knee arthroplasty (TKA) was available for the analysis. For each case, knee surface models derived from CT as well as coordinates of the hip and ankle joint centers were available. Eight interbone parameters of the knee were identified in a literature research and an existing framework for morphological analysis of the knee was extended, in order to automatically calculate those parameters.

The interbone analysis succeeded for 405 (97.8%) cases. After the exclusion of implausible cases, 373 (90.1%) parameter sets remained for statistical analysis.

Differences in methodology, populations, imaging technique etc. complicate the comparison with values from the literature. However, for similar studies a good agreement in parameter values was found.

The workflow presented proved robust against a large dataset of knee surface models. In the future, information about the bones' relative position in the active, weight-bearing situation should be incorporated, in order to assess the impact on knee interbone parameters.

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1 Introduction

Interbone parameters of the knee, such as the tibial tuberosity to trochlear groove (TT-TG) distance, are frequently used in clinical practice in order to assess the functional anatomy of the individual patient. They can also be used as indicators for functional disorders, such as patellar instability (Dejour et al. 1994; Steensen et al. 2015). With three-dimensional (3D) surface data of the knee, derived e.g. from computed tomography (CT), a comprehensive analysis regarding various interbone parameters is possible (Fürmetz et al. 2021). However, the identification of landmarks is mostly done manually and the parameter calculation is often not automated, which leads to a time-consuming process. For the identification of parameter reference ranges or safe zones, the consideration of large databases is favorable. Therefore, the aim of this study was to automate the derivation of interbone parameters from 3D surface data of the knee and to evaluate the method's robustness against a large dataset.

2 Materials and Methods

A dataset of 414 knees from patients scheduled for total knee arthroplasty (TKA) was available for the analysis, of which 164 were male and 248 were female. For two knees, no gender information was present. For each case, surface models of femur, tibia and patella and the coordinates of the hip and ankle joint center were available. The surface models were derived previously from CT images, with the patient in supine position. This is a relevant limitation, since the relative position of the bones may differ significantly between the weight-bearing and non-weight-bearing situation. However, CT is the gold standard for the measurement of bone morphology and some authors question whether the limitation of a non-weight-bearing measurement is of clinical relevance (Hirschmann et al. 2019). In the future, the impact of weight-bearing on knee interbone parameter measurements should be evaluated e.g. through 3D2D referencing of the surface models with EOS images. The presented automated interbone analysis can be applied either way, both with and without prior referencing.

In a literature research, 8 interbone parameters of the knee were identified, which can be evaluated based on CT data: the patellar tilt and shift, the congruence angle, the TT-TG distance both absolute and relative, the joint rotation, the hip knee angle and the Insall Salvati index. Both for the patellar tilt and patellar shift, various definitions exist in the literature (Patellar tilt: (Alemparte et al. 2007; Collado and Fredericson 2010; Laurin et al. 1978), Patellar shift: (Chia et al. 2009; Nicolaas et al. 2011; Zhang et al. 2017)). For the patellar tilt we chose the definition described from both Laurin et al. (Laurin et al. 1978) and Davies et al. (Davies et al. 2000). Regarding the patella shift, we chose the definition from Chia et al. (Chia et al. 2009). In addition, in the literature different measures are used for the normalization of the TT-TG distance. Hingelbaum et al. (Hingelbaum et al. 2014) used the the proximodistal distance of the entrance of the trochlear groove to the insertion of the patellar tendon at the tibial tubercle. Balcarek et al. (Balcarek et al. 2011) used the epicondylar distance, parallel to the femoral posterior condylar line. In our study, we used the femoral epicondylar width for the normalization. Regarding the other parameters, there was consensus or prevailing opinion as to their definition.

An existing framework for the evaluation of individual bone morphology of femur, tibia and patella was extended for the calculation of respective interbone parameters. The workflow was initialized with reading meta-information about the patient before the morphological analysis started. First, the morphology of each bone was analyzed individually as described in previous studies (Asseln et al. 2018; Asseln and Radermacher 2019). During the process, the bone's polygon mesh was imported and transformed into a bone specific coordinate system (COS) and morphologic parameters were derived. Relevant landmarks as well as the transformations from the CT to the bone-specific

COS were saved. After completion of the bone-specific morphological analyses, the interbone analysis was performed, as this meant that already defined landmarks of the bones could be used. Since the meshes and landmarks were stored in their specific COS, for the calculation of each interbone parameter the meshes and landmarks required had to be transformed into a chosen COS. For example, the femoral COS was chosen for TT-TG distance, so the tibial mesh and the coordinates of the tibial tuberosity were transformed from the tibial COS to the femoral COS. Reference points and reference lines used for the calculation of the interbone parameters are presented in **Figure 1**.

The plausibility of the bone-specific parameters was evaluated based on values from literature, as described in a previous study (Asseln et al. 2018). Since the interbone parameters depend on landmarks derived in the bone-specific morphological analyses, they were also evaluated as implausible if any of the bone-specific parameter sets were evaluated as such. In addition, the plausibility of the interbone parameters was evaluated, based on a box plot outlier assessment. For all plausible interbone parameter sets, mean and standard deviations were calculated, both for male and female cases separately as well as combined.

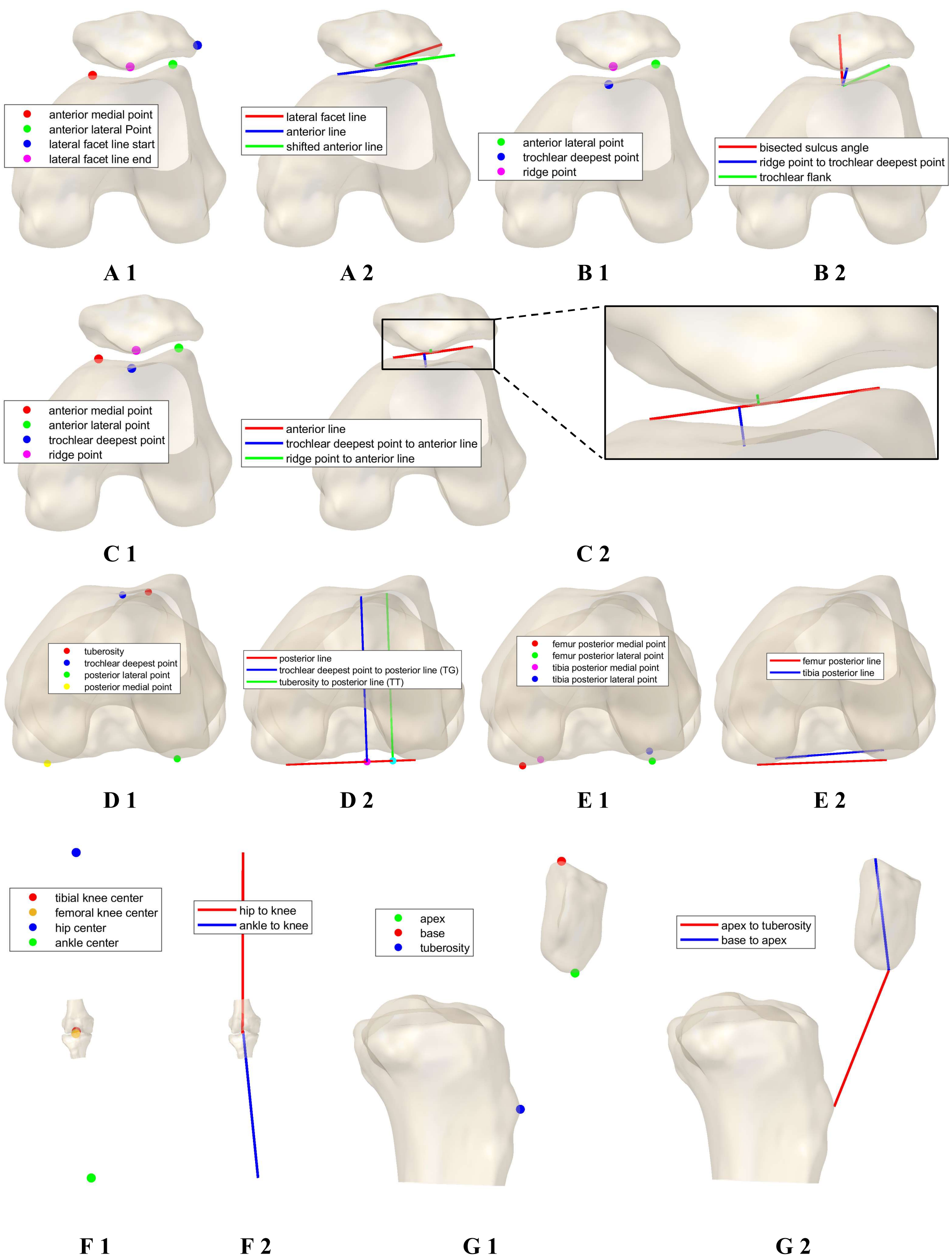

Figure 1: Reference points (1) and reference lines (2) for the calculation of interbone parameters as implemented in the automated morphological analysis. A: Patellar tilt. B: Congruence angle. C: Patellar shift. D: TT-TG distance. E: Joint rotation. F: Hip knee angle. G: Insall Salvati index.

3 Results

411 (99.3%) femora, 409 (98.8%) tibiae and all patellae (100%) could be processed without error. The interbone workflow succeeded for 405 (98.3%) cases. 380 (92.5%) femora, 347 (84.8%) tibiae and 410 (99.0%) patellae passed the plausibility check. After the exclusion of implausible cases, either due to exceeding of bone specific parameter ranges or due to classification as outliers in the box plot assessment, 373 cases remained (225 female, 147 male, 1 without gender information), which were used for statistical evaluation. Respective results are listed in **Table 1**.

Table 1: Results of the statistical analysis of interbone parameters from 373 cases.

Parameter	Combined	Female	Male
		Mean ± SD	
Patellar tilt	4.82° ± 6.50°	4.80° ± 6.90°	4.85° ± 5.90°
Patellar shift	3.72 mm ± 3.11 mm	3.39 mm ± 3.03 mm	4.25 mm ± 3.17 mm
Congruence angle	20.21° ± 18.82°	19.69° ± 20.28°	21.13° ± 16.36°
TT-TG	12.19 mm ± 5.46 mm	11.91 mm ± 5.31 mm	12.64 mm ± 5.70 mm
Relative TT-TG	0.15 ± 0.07	0.15 ± 0.07	0.14 ± 0.07
Joint rotation	2.67° ± 3.91°	2.71° ± 3.764°	2.63° ± 4.15°
Hip knee angle	175.7° ± 5.1°	176.5° ± 5.0°	174.4° ± 5.0°
Insall Salvati index (3D)	1.35 ± 0.22	1.34 ± 0.22	1.36 ± 0.23

4 Discussion

The workflow demonstrated to be feasible for the automated analysis of a large dataset of knee surface models. For verification purposes, we aimed to compare our results with those of studies with a similar patient population (OA/TKA patients), imaging technique (CT) and parameter definition if available.

Alemparte et al. (Alemparte et al. 2007) analyzed asymptomatic knees regarding the patellar tilt according to the definition of Laurin et al. (Laurin et al. 1978)/ Davies et al. (Davies et al. 2000) and found a mean value of 8.1° ± 14.5° for CT data. The mean value in our study was smaller (combined: 4.82°) and the standard deviation was much reduced (combined: 6.50°). The difference in mean value and standard deviation could be due to the different study populations (control vs. OA). In the case of isolated lateral patellofemoral OA, the patellar tilt could be reduced. This could explain the lower mean patellar tilt in our study of OA patients. A second explanation for the difference in standard deviation could be the difference in landmark detection, which was automated in our workflow and manual in the study of Alemparte et al.

In our study we used the patellar shift definition described by Chia et al. (Chia et al. 2009), which was also used by Zhang et al. (Zhang et al. 2017). Zhang et al. found a mean patellar tilt of 3.2 mm ± 3.8 mm for knees with patellofemoral OA based on X-rays. Chia et al. (Chia et al. 2009) found a mean patellar shift of 5.7 mm ± 4.6 mm in patients scheduled for TKA measured on X-rays. In our study, a patellar shift of 3.72 mm ± 3.11 mm was found for the combined population, which is in agreement with the previous studies.

Zhang et al. (Zhang et al. 2017) investigated the congruence angle of OA patients and found a mean value of 27.9° ± 29.9°. In our study, we found a mean congruence angle of 20.21° ± 18.82°. An explanation for this difference may be found in the imaging technique. Zhang et al. used standard X-rays for their evaluation, while we used surface models. In the patella skyline view, the deepest point of the sulcus may be obscured due to projection (**Figure 1-B1**), whereby the deepest point would be estimated to be closer to the patellar ridge. For the same anatomy, this would lead to the higher congruence angle.

Various groups have reported mean values for the TT-TG distance (Balcarek et al. 2011; Dejour et al. 1994). Hochreiter et al. (Hochreiter et al. 2019) also analyzed patients scheduled for TKA and found a mean TT-TG of 12.9 mm ± 5.6 mm based on CT data. We found a mean value of 12.19 mm ± 5.46 mm, which is in good agreement with the results of Hochreiter et al., regarding both mean value and standard deviation.

Balcarek et al. (Balcarek et al. 2011) calculated the relative TT-TG distance in a control group, and found a mean value of 0.14 ± 0.05. In our study, we found a mean value for the combined population of 0.15 ± 0.07, which is in agreement with the results of Balcarek et al.

Tensho et al. (Tensho et al. 2015) found a mean joint rotation of 4.0° ± 3.7° in a control group analyzed by CT. Seitlinger et al. (Seitlinger et al. 2012) also analyzed a control group in their study, and found a mean joint rotation of 2.632° ± 3.143° based on MRI images. Our results regarding the joint rotation are comparable (combined: 2.67° ± 3.91°), despite the different study populations.

Fürmetz et al. (Fürmetz et al. 2021) evaluated the Insall Salvati index in 3D based on CT data from healthy subjects. They determined a reference range of 1.0 - 1.4. Our mean values are within the given reference range, however, at its upper limit.

The mean leg alignment of patients undergoing TKA is reported to be slightly varus (HKA < 180°) (Hirschmann et al. 2019; Seitlinger et al. 2012). With a mean HKA below 180° for all groups, this was supported by our results. In our study, the hip knee angle was higher for female compared to male cases, which is also consistent with the literature (Gschöpf 2013; Hirschmann et al. 2019).

Summarizing the comparison with the literature, we found similar interbone parameter values, especially for studies on TKA patients. A relevant limitation of our study is that the CT was taken with the patients in supine position. The interbone parameters derived from the supine position, may differ significantly from those in the relevant weight-bearing situation. However, it has to be noted that similar CT studies cited in this article share this limitation. In the future, the influence of weight-bearing on knee interbone parameter measurements should be identified, e.g. by 3D2D referencing of the surface models with EOS images. If the effects are clinically relevant, such referencing should be incorporated in the process. As an alternative, other imaging techniques could be considered, such as weight-bearing cone beam CT (Thawait et al. 2015).

Disclosures

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References

Alemparte J, Ekdahl M, Burnier L, Hernández R, Cardemil A, Cielo R, Danilla S (2007) Patellofemoral evaluation with radiographs and computed tomography scans in 60 knees of asymptomatic subjects. Arthroscopy 23:170–177. https://doi.org/10.1016/j.arthro.2006.08.022

Asseln M, Radermacher K (2019) Automatic analysis of morphological parameters of the patella based on three-dimensional (3D) surface data. In: EasyChair, 31-25

Asseln M, Hänisch C, Schick F, Radermacher K (2018) Gender differences in knee morphology and the prospects for implant design in total knee replacement. Knee 25:545–558. https://doi.org/10.1016/j.knee.2018.04.005

Balcarek P, Jung K, Frosch K-H, Stürmer KM (2011) Value of the tibial tuberosity-trochlear groove distance in patellar instability in the young athlete. Am J Sports Med 39:1756–1761. https://doi.org/10.1177/0363546511404883

Chia S-L, Merican AM, Devadasan B, Strachan RK, Amis AA (2009) Radiographic features predictive of patellar maltracking during total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc 17:1217–1224. https://doi.org/10.1007/s00167-009-0832-y

Collado H, Fredericson M (2010) Patellofemoral pain syndrome. Clin Sports Med 29:379–398. https://doi.org/10.1016/j.csm.2010.03.012

Davies AP, Costa ML, Shepstone L, Glasgow MM, Donell S, Donnell ST (2000) The sulcus angle and malalignment of the extensor mechanism of the knee. J Bone Joint Surg Br 82:1162–1166. https://doi.org/10.1302/0301-620X.82B8.10833

Dejour H, Walch G, Nove-Josserand L, Guier C (1994) Factors of patellar instability: an anatomic radiographic study. Knee Surg Sports Traumatol Arthrosc 2:19–26. https://doi.org/10.1007/bf01552649

Fürmetz J, Daniel T, Sass J, Bergsträßer M, Degen N, Suero E, Ahrens P, Keppler AM, Böcker W, Thaller PH, Prall WC (2021) Three-dimensional assessment of patellofemoral anatomy: Reliability and reference ranges. Knee 29:271–279. https://doi.org/10.1016/j.knee.2021.02.016

Gschöpf B (2013) Geschlechterspezifische Unterschiede in der nativradiologischen Ausprägung der Gonarthrose zum Zeitpunkt des endoprothetischen Kniegelenkersatzes.

Hingelbaum S, Best R, Huth J, Wagner D, Bauer G, Mauch F (2014) The TT-TG Index: a new knee size adjusted measure method to determine the TT-TG distance. Knee Surg Sports Traumatol Arthrosc 22:2388–2395. https://doi.org/10.1007/s00167-014-3204-1

Hirschmann MT, Hess S, Behrend H, Amsler F, Leclercq V, Moser LB (2019) Phenotyping of hip-knee-ankle angle in young non-osteoarthritic knees provides better understanding of native alignment variability. Knee Surg Sports Traumatol Arthrosc 27:1378–1384. https://doi.org/10.1007/s00167-019-05507-1

Hochreiter B, Hirschmann MT, Amsler F, Behrend H (2019) Highly variable tibial tubercle-trochlear groove distance (TT-TG) in osteoarthritic knees should be considered when performing TKA. Knee Surg Sports Traumatol Arthrosc 27:1403–1409. https://doi.org/10.1007/s00167-018-5141-x

Laurin CA, Lévesque HP, Dussault R, Labelle H, Peides JP (1978) The abnormal lateral patellofemoral angle: a diagnostic roentgenographic sign of recurrent patellar subluxation. J Bone Joint Surg Am 60:55–60

Nicolaas L, Tigchelaar S, Koëter S (2011) Patellofemoral evaluation with magnetic resonance imaging in 51 knees of asymptomatic subjects. Knee Surg Sports Traumatol Arthrosc 19:1735–1739. https://doi.org/10.1007/s00167-011-1508-y

Seitlinger G, Scheurecker G, Högler R, Labey L, Innocenti B, Hofmann S (2012) Tibial tubercle-posterior cruciate ligament distance: a new measurement to define the position of the tibial tubercle in patients with patellar dislocation. Am J Sports Med 40:1119–1125. https://doi.org/10.1177/0363546512438762

Steensen RN, Bentley JC, Trinh TQ, Backes JR, Wiltfong RE (2015) The prevalence and combined prevalences of anatomic factors associated with recurrent patellar dislocation: a magnetic resonance imaging study. Am J Sports Med 43:921–927. https://doi.org/10.1177/0363546514563904

Tensho K, Akaoka Y, Shimodaira H, Takanashi S, Ikegami S, Kato H, Saito N (2015) What Components Comprise the Measurement of the Tibial Tuberosity-Trochlear Groove Distance in a Patellar Dislocation Population? J Bone Joint Surg Am 97:1441–1448. https://doi.org/10.2106/JBJS.N.01313

Thawait GK, Demehri S, AlMuhit A, Zbijweski W, Yorkston J, Del Grande F, Zikria B, Carrino JA, Siewerdsen JH (2015) Extremity cone-beam CT for evaluation of medial tibiofemoral

osteoarthritis: Initial experience in imaging of the weight-bearing and non-weight-bearing knee. Eur J Radiol 84:2564–2570. https://doi.org/10.1016/j.ejrad.2015.09.003
Zhang X, Eyles JP, Makovey J, Williams MJ, Hunter DJ (2017) Is the effectiveness of patellofemoral bracing modified by patellofemoral alignment and trochlear morphology? BMC Musculoskelet Disord 18:168. https://doi.org/10.1186/s12891-017-1524-2