Eur Radiol (2015) 25:3398–3404
DOI 10.1007/s00330-015-3756-6

MUSCULOSKELETAL

Upright CT of the knee: the effect of weight-bearing on joint alignment

Anna Hirschmann [1,3] · Florian M. Buck [1] · Sandro F. Fucentese [2] · Christian W. A. Pfirrmann [1]

Received: 30 July 2014 / Revised: 24 March 2015 / Accepted: 30 March 2015 / Published online: 1 May 2015

Abstract
Objectives To prospectively compare patellofemoral and femorotibial alignment in supine non-weight-bearing computed tomography (NWBCT) and upright weight-bearing CT (WBCT) and assess the differences in joint alignment.
Methods NWBCT and WBCT images of the knee were obtained in 26 patients (mean age, 57.0±15.9 years; range, 21-81) using multiple detector CT for NWBCT and cone-beam extremity CT for WBCT. Two musculoskeletal radiologists independently quantified joint alignment by measuring femorotibial rotation, tibial tuberosity-trochlear groove distance (TTTG), lateral patellar tilt angle, lateral patellar shift, and medial and lateral femorotibial joint space widths. Significant differences between NWBCT and WBCT were sought using Wilcoxon signed-rank test (P-value<0.05).
Results Significant differences were found for femorotibial rotation (the NWBCT mean changed from 2.7°±5.1 (reader 1)/2.6°±5.6 (reader 2) external rotation to WBCT 0.4°±7.7/0.2°±7.5 internal rotation; P=0.009/P=0.004), TTTG (decrease from NWBCT (13.8 mm±5.1/13.9 mm±3.9) to WBCT (10.5 mm±5.0/10.9 mm±5.2; P=0.008/P=0.002), lateral patellar tilt angle (decrease from NWBCT (15.6°±6.7/16.9°±7.4) to WBCT (12.5°±7.7/15.0°±6.2; P=0.011/P=0.188). The medial femorotibial joint space decreased from NWBCT (3.9 mm±1.4/4.5 mm±1.3) to WBCT (2.9 mm±2.2/3.5 mm±2.2; P=0.003/P=0.004). Inter-reader agreement ranged from 0.52-0.97.
Conclusion Knee joint alignment changes significantly in the upright weight-bearing position using CT when compared to supine non-weight-bearing CT.
Key Points
- *Cone-beam extremity CT offers upright weight-bearing examinations of the lower extremities.*
- *Knee alignment changes significantly in an upright position compared to supine position.*
- *Tibial tuberosity-trochlear groove distance (TTTG) is less pronounced in a weight-bearing position.*
- *The weight-bearing position leads to a decrease of the lateral patellar tilt angle.*

Keywords Cone-beam extremity CT · Upright weight-bearing CT · Knee alignment · Tibial tuberosity-trochlear groove (TTTG) · Lateral patellar tilt angle

✉ Anna Hirschmann
anna.hirschmann@usb.ch

1 Department of Radiology, Orthopedic University Hospital Balgrist, University of Zurich, Forchstrasse 340, 8008 Zurich, Switzerland

2 Orthopedic Surgery, Orthopedic University Hospital Balgrist, University of Zurich, Forchstrasse 340, 8008 Zurich, Switzerland

3 Clinic of Radiology and Nuclear Medicine, University of Basel Hospital, Petersgraben 4, 4031 Basel, Switzerland

Introduction

The knee joint has been well investigated using conventional weight-bearing radiographs, however, X-rays are limited to 2D imaging. Computed tomography (CT) with multi-planar reformations or magnetic resonance tomography (MR) in different planes are necessary for precise evaluation of certain parameters of the femorotibial and patellofemoral alignment, such as femorotibial rotation and tibial tuberosity-trochlear groove (TTTG) distance. Only a few studies have addressed investigations of the knee joint using weight-bearing MR [1–10], mainly in the supine position with special devices [4, 7, 8] and regarding the patellofemoral joint. As such, the understanding of the physiologic alignment of the patellofemoral and femorotibial joints in the upright weight-bearing position is still limited. Certain cone-beam CT systems allow examinations of the knee joint in the upright weight-bearing position [11, 12]. In daily practice, cross sectional images of the knee joint are limited to the supine, non-weight-bearing position. Changes in joint alignment on cross sectional images between non-weight-bearing and weight-bearing positions are unknown. Thus, the purpose of this study was to prospectively compare patellofemoral and femorotibial joint alignment in standard supine non-weight-bearing CT (NWBCT) and upright weight-bearing CT (WBCT) and assess the differences in joint alignment.

Materials and methods

Patient and CT technique

Institutional review board approval and informed consent of all patients were obtained. NWBCT and WBCT images of the knee were obtained in 26 patients (mean age, 57.0±15.9 years; range, 21-81 years; 15 women; mean age, 58.6±14.2 years; range, 21-76 years; 11 men; mean age, 54.8±18.5 years; range, 23-81 years) using a standard 64-slice multi-detector CT (Brilliance 64, Philips Healthcare, Best, Netherlands) for NWBCT and a novel cone-beam extremity CT for WBCT (Planmed Verity Extremity Scanner, Planmed Oy, Helsinki, Finland). Imaging was performed on the same day.

For both examinations the knee was in the fully extended position. For the upright WBCT examination, the patient was standing on the foot of the examined leg. The other knee was bent resting outside the gantry (Fig. 1). Axial images of the knee joint were acquired (NWBCT: tube voltage, 120 kV; tube current, 150 mAs/slice; pitch factor, 0.671; $CTDI_{vol}$, 12.1 mGy; matrix, 512×512; reconstruction thickness, 0.9 mm; reconstruction increment, 0.45 mm; scan time, 9 s; WBCT: tube voltage, 96 kV; tube current, 7.5 mAs; $CTDI_{vol}$, 4.3 mGy; matrix, 160×160×130; pixel size, 0.4 mm; slice interval, 0.4 mm; scan time 18 s). Axial (reconstruction thickness, 2 mm), sagittal (reconstruction thickness, 2 mm) and coronal (reconstruction thickness, 2 mm) bone window reformations were used for measurements.

All patients included in this study were referred from an orthopaedic department with a clinical indication for a CT of the knee due to pain. Indications for the CT were osteoarthritis of the knee (n=17), follow up of anterior cruciate ligament (ACL) graft (n=3) and others (n=6), including healed fracture of the intercondylar eminence (n=1), avascular necrosis of the medial femoral condyle (n=4), and a soft tissue tumour (n=1). Patients were included if they were able to fully bear weight on the examined leg. Patients were excluded if they were under the age of 18 and if they did not give informed consent.

CT analysis

Two musculoskeletal radiologists independently performed the following measurements on NWBCT and WBCT: femorotibial rotation, TTTG, lateral patellar tilt angle, lateral patellar shift, and medial and lateral femorotibial joint space widths.

The femorotibial rotation angle was measured on axial slices by a line parallel to the most posterior part of the femoral condyles and a line parallel to the posterior osseous contour of the tibial plateau (Fig. 2) [13]. Internal, as well as external, femorotibial rotation was defined as a rotation of the tibial plateau in relation to the femoral condyles.

For the TTTG distance, a reference line parallel to the posterior femoral condyles three centimetres above the femorotibial joint space was used to draw a line perpendicular to the deepest point of the trochlea [14]. The distance from the

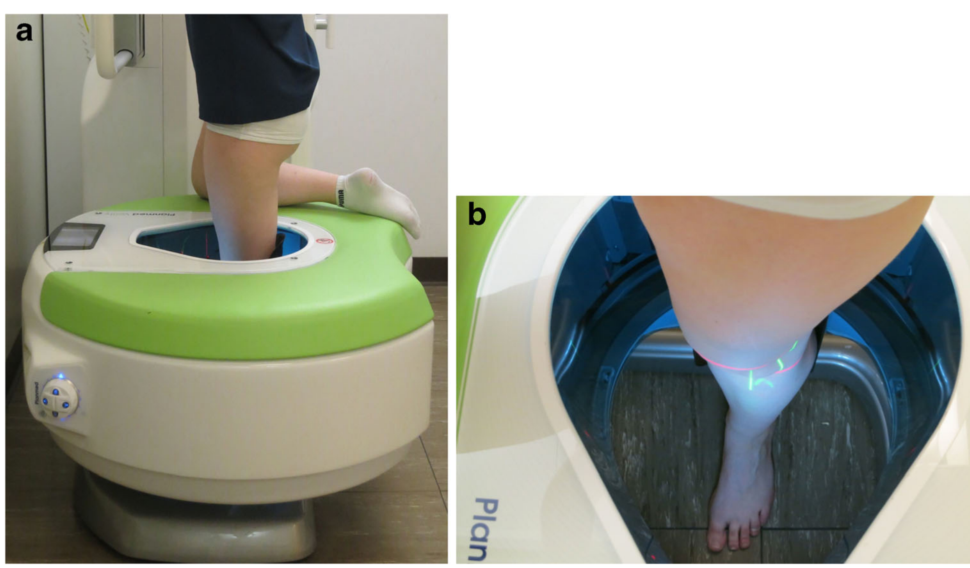

Fig. 1 Photographs of the position during upright weight-bearing knee examination using cone-beam CT

Fig. 2 21-year-old female with a follow up of a 9-month-old fracture of the intercondylar eminence of the left knee joint. Femorotibial rotation changed from 7° external rotation in NWBCT (**a**) to 4° internal rotation in WBCT (**b**). Axial slices (2 mm slice thickness) were rotated with a horizontal orientation of the posterior femoral condyles for better visualization of the femorotibial rotation in NWBCT and WBCT

deepest point of the trochlea to the midpoint of the tibial tuberosity at the level of the patella tendon insertion was measured parallel to the reference line to measure the TTTG distance on axial images (Fig. 3) [15].

For the lateral patellar tilt angle, the axial image at the largest width of the patella was used. A line through the medial and lateral borders of the patella was drawn, as well as a line through the anterior border of the femoral condyles (Fig. 4) [13, 16].

For the lateral patellar shift, the axial image at the largest width of the patella was chosen. A line paralleling the anterior border of the femoral trochlea was drawn as a reference line. Along this line, the distance between the deepest point of the trochlea and the most posterior point of the patellar surface was measured (Fig. 5) [17].

The medial and lateral femorotibial joint space widths were measured on coronal images at the midpoint of the medial and lateral femorotibial compartment.

Statistical analysis

Descriptive statistics were used to report the quantitative data. The Wilcoxon signed-rank test was utilized to assess significant changes between NWBCT and WBCT. Inter-reader agreement was assessed using an intra-class correlation coefficient (ICC). According to Rosner [18], the inter-reader reliability by means of ICC is classified as follows: > 0.75 is excellent, 0.4-0.75 is fair to good, and < 0.4 is poor. A *P*-value of less than 0.05 was considered statistically significant. For all analyses, SPSS software (release 17.0; SPSS, Chicago, IL, USA) was used.

Results

The quantitative results of both readers are shown in Table 1.

Significant differences between NWBCT and WBCT were found for the femorotibial rotation, the TTTG, the lateral patellar tilt angle, and the medial joint space width (Table 1). Comparing WBCT with NWBCT, femorotibial rotation changed from an external rotation in the supine position to a slight internal rotation in the upright position (mean difference reader 1/reader 2; 3.1°/2.8°; Fig. 2). The TTTG decreased significantly in WBCT (3.3 mm/3.0 mm) for both readers (Fig. 3), and the lateral patellar tilt angle decreased significantly in WBCT (3.1°/1.9°) for reader 1 (but $P=0.188$ for reader 2) (Fig. 4). The medial joint space width decreased significantly in WBCT (1.0 mm, respectively; Fig. 6). Lateral patellar shift increased (0.4 mm, respectively) and lateral joint space width decreased (0.2 mm/0.4 mm) from NWBCT to WBCT,

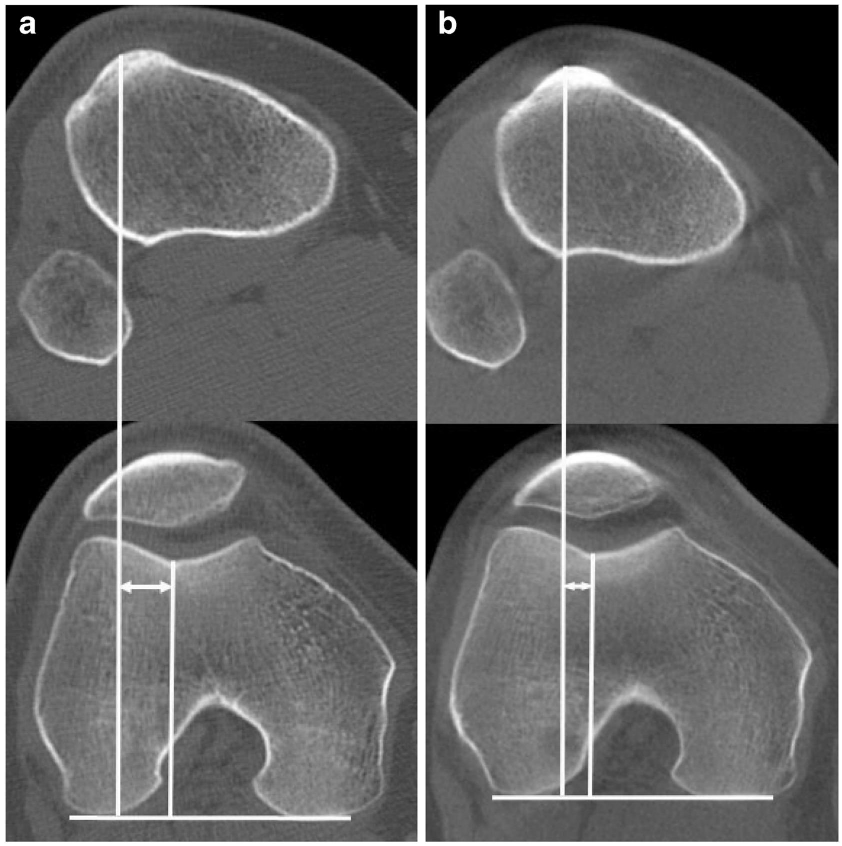

Fig. 3 31-year-old female with osteonecrosis of the right medial femoral condyle (not shown). (**a**) and (**b**), axial images (2 mm slice thickness) of the knee joint show the measurement technique of the TTTG (tibial tuberosity-trochlear groove distance). The TTTG decreased from NWBCT (**a**, 15 mm) to WBCT (**b**, 7 mm), as shown on the images

without significant differences for both readers (Table 1). Inter-reader agreement ranged from 0.52 - 0.97 (Table 2).

Discussion

Routine cross sectional imaging, such as CT or MR, only allows examinations of the lower extremity in the supine position. Only a few MR systems offer upright weight-bearing examinations of the lower extremities [2, 3, 10], mainly provided by special devices to simulate weight-bearing either in the supine position [4, 7, 8] or in a semi-upright position [1, 5, 6]. For CT, usually, no real physiological weight-bearing examinations are possible [19]. The recent introduction of a new scanner design, the cone-beam extremity CT used for this study, allows upright weight-bearing images of the lower extremity under physiological loading conditions [11, 12, 20]. We assessed the knee joint alignment in two positions, the

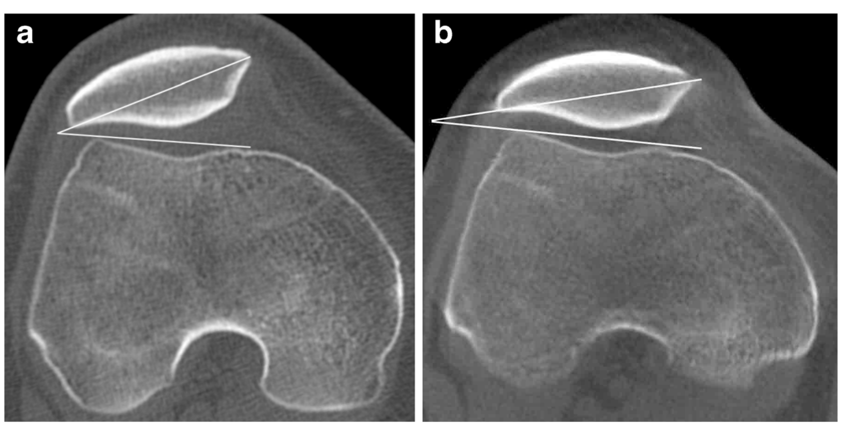

Fig. 4 31-year-old male with a follow up CT examination of a proximal tibial fracture of the right side. The lateral patellar tilt angle was defined according to Sasaki [16], as the angle between a line through the medial and lateral contour of the patella and a line adapted to the anterior contour of the femoral trochlea. The axial image (2 mm slice thickness) at the largest width of the patella was used. A decrease of the lateral patellar tilt angle from NWBCT (**a**, 20°) to WBCT (**b**, 9°) was found

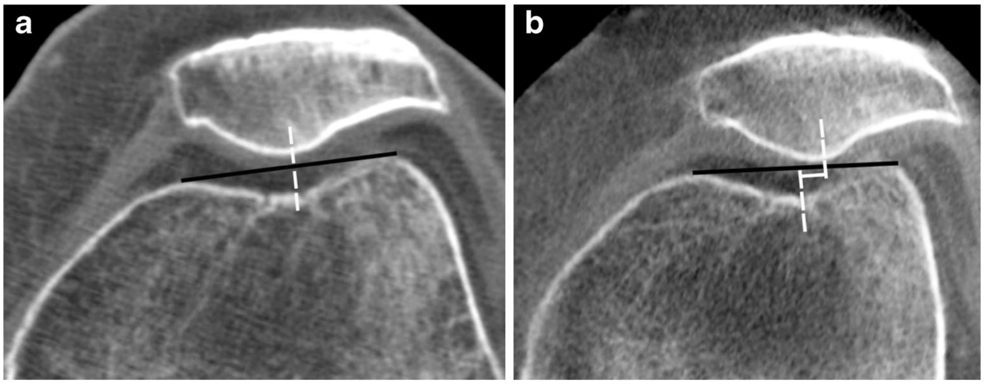

Fig. 5 76-year-old female with osteoarthritis of the left knee joint. For the lateral patellar shift, the distance between the deepest point of the trochlea (dashed line) and the most posterior point of the patella (dashed line) was measured along a reference line (black line) at the anterior border of the femoral trochlea. The lateral patellar shift slightly increased in this patient from NWBCT (**a**, 0 mm) to WBCT (**b**, 4 mm), although the mean results of our study were not significant (*P*=0.83/0.79)

supine non-weight-bearing and the upright weight-bearing position. Clinically significant differences in the weight-bearing position were found for the femorotibial rotation, the TTTG, the lateral patellar tilt angle, and the medial femorotibial joint space width. Excellent inter-reader agreement for a majority of the measurements demonstrates the high reproducibility of the measurement methods.

The lateral patellar tilt decreased significantly in the WBCT (12.5°) compared to NWBCT (15.6°) for reader 1. So far, no study has evaluated the lateral patellar tilt angle, with a line through the medial and lateral borders of the patella and a line through the anterior border of the femoral condyles, in the upright position. Powers et al. [2] compared the patellofemoral alignment of six patients with patellofemoral pain using kinematic MR in a non-weight-bearing sitting position and upright position with knee flexion from 0° to 45° with results equal to our study. Contraction of the quadriceps muscle, especially the vastus medialis muscle, which is a dynamic stabilizer of the patella, leads to a decrease of the lateral patellar tilt angle [8]. It is known from the literature that the internal tibial rotation in WBCT might as well contribute to the decrease of the lateral patellar tilt. Lin et al. discovered no change of the lateral patellar tilt angle with any change in femoral or tibial rotation using the anterior border of the femoral condyle for measurement, while using the posterior border of the femoral condyle, the patellar tilt angle decreased with increasing internal tibial rotation in relation to the femur [13]. This knowledge was the main reason for choosing the anterior border of the femoral condyle as a reference line for the lateral patellar tilt angle in our study. Hence, the decrease of the lateral patellar tilt angle in the weight-bearing position is supposed to be a true finding, as the femur is rotating underneath the patella [13]. In earlier years, van Kampen and Huiskes [21] reported that femoral and tibial rotation influences patellar tracking, especially in knee extension and the first degrees of knee flexion.

The change of the femorotibial rotation from external rotation in NWBCT to internal rotation in WBCT may lead to a decrease of the TTTG in WBCT; both mechanisms were consistent with the results of our study. Izadpanah et al. [10] likewise reported a decrease of the TTTG from the supine to the upright position using MR. However, the TTTG distances, especially in the upright position were different to our results:

Table 1 Quantitative analysis of the knee joint alignment in supine non-weight-bearing computed tomography (NWBCT) and upright weight-bearing computed tomography (WBCT)

	Reader 1			Reader 2		
	NWBCT	WBCT	*P* value	NWBCT	WBCT	*P* value
Femorotibial rotation [°]	2.7±5.1 ER	0.4±7.7 IR	0.009*	2.6±5.6 ER	0.2±7.5 IR	0.004*
TTTG [mm]	13.8±5.1	10.5±5.0	0.008*	13.9±3.9	10.9±5.2	0.002*
Lateral patellar tilt angle [°]	15.6±6.7	12.5±7.7	0.011*	16.9±7.4	15.0±6.2	0.188
Lateral patellar shift [mm]	0.8±3.7	1.2±4.5	0.83	0.9±3.4	1.3±3.7	0.79
Medial joint space width [mm]	3.9±1.4	2.9±2.2	0.003*	4.5±1.3	3.5±2.2	0.004*
Lateral joint space width [mm]	4.7±1.5	4.5±2.1	0.57	5.6±1.5	5.2±2.1	0.078

Data are mean values with standard deviations.

*A *P* value<0.05 was considered statistically significant.

*ER= external rotation. IR= internal rotation. TTTG=*tibial tuberosity-trochlear groove distance.

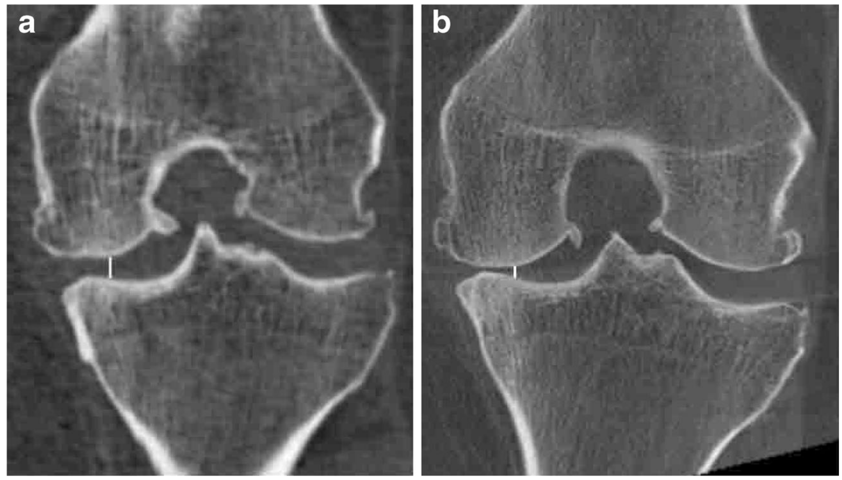

Fig. 6 68-year-old female with osteoarthritis of the knee joint. Medial and lateral femorotibial joint space widths were measured in the midline of the joint on a coronal image. The medial joint space width decreased from NWBCT (**a**, 4 mm) to WBCT (**b**, 0.5 mm)

In our study, the mean TTTG in the upright position was 10.5 – 10.9 mm, while in the study of Izadpanah et al. [10], the mean TTTG distance was only 6.3 mm. Assessment of the TTTG with different modalities such as MR and CT may vary, as shown by Schoettle et al. [15] and Camp et al. [22]. The main reason for different TTTG values within or between modalities is the technique of TTTG measurement as well as the degree of extension or flexion of the knee, as shown by Dietrich et al. [23]. Determination of precise axial images for assessment of the trochlea groove as well the tibial tuberosity is challenging. Identifying the most proximal image with a complete cartilaginous trochlea is difficult due to the thin cartilage layer and the low contrast differences between cartilage and synovium. Avoiding error in measurement, we chose a modified method, selecting the trochlea depth for the TTTG three centimetres above the joint line according to Pfirrmann et al. [14]. Furthermore, we have remarked inaccuracies in selecting the most anterior point of the tibial tuberosity, as suggested by Schoettle [15], since this anatomical landmark is mostly flat. Therefore, we chose the midpoint of the tibial tuberosity at the level of the patella tendon insertion.

Table 2 Inter-reader agreement of the knee joint alignment in supine non-weight-bearing computed tomography (NWBCT) and upright weight-bearing computed tomography (WBCT)

	NWBCT	WBCT
Femorotibial rotation	0.90	0.97
TTTG	0.52	0.77
Lateral patellar tilt angle	0.88	0.64
Lateral patellar shift	0.78	0.79
Medial joint space width	0.80	0.90
Lateral joint space width	0.69	0.79

Intra-class correlation coefficient (ICC) according to Rosner [18]: >0.75 excellent, 0.4 - 0.75 fair to good, <0.4 poor

TTTG=tibial tuberosity-trochlear groove distance.

Izadpanah et al. [10] selected the depth of the trochlea groove at the most proximal axial image with complete cartilaginous coverage as described earlier by Schoettle et al. [15], which is slightly more proximal than 3 cm above the joint line. Nevertheless, our mean TTTG of 10.5 - 10.9 mm in the upright position is in the range of normal TTTG values, which is less than 15 – 20 mm [24, 25].

Although not significant, a slightly higher lateral patellar shift was seen with WBCT. This finding is in accordance with the results of a kinematic MR study by Powers et al. [2]. They also reported no significant difference of the lateral patellar shift between non-weight-bearing sitting and the upright weight-bearing position with a more pronounced shift in the weight-bearing position. The mean lateral patellar shift in the upright position (1.2 - 1.3 mm) was slightly higher compared to the results of Tennant et al. with 0.4 mm [9]. Again, internal femorotibial rotation in the upright position may influence the lateral patellar shift, a similar phenomenon seen with the lateral patellar tilt angle. These results are consistent with observations of Powers et al. and Tennant et al. [2, 9].

The significant decrease of the medial joint space width in the upright position is a phenomenon of weight-bearing and might be pronounced in varus-aligned knees or in severe osteoarthritis. With increasing age, the prevalence of osteoarthritis of the knee joint increases, hence, osteoarthritis was evident in the majority of our rather elderly study population with a mean age of 57 years. A decrease of all joint space widths of the lower extremity in the upright weight-bearing position is a known phenomenon, although the decrease of the lateral femorotibial joint space width was not statistically significant, it was slightly less than in the supine position. Certainly, severe valgus-osteoarthritis knees may have a more pronounced lateral joint space narrowing under weight-bearing conditions.

The significant differences in knee joint alignment with upright weight-bearing imaging illustrate a potential method and the need for a natural and physiological position to evaluate the knee joint using cross-sectional imaging for a better understanding of the biomechanics and a precise planning for surgical therapy. Weight-bearing CT, in contrast to X-ray, has the potential to more precisely assess knee joint alignment. However, X-ray is a common method and has the advantages of cost-efficiency and widespread availability, a tool sufficient for baseline examination of the knee joint. The significantly lower values of the lateral patellar shift and the TTTG raises the question of new thresholds for examinations under physiological upright weight-bearing conditions evaluating patellofemoral diseases.

Limitations of our study are the limited number of patients (26), mainly presented with osteoarthritis of the knee joint; changes between non-weight-bearing and weight-bearing might be related to the underlying disease of this population. Hence, our results, especially concerning patellofemoral changes, may not apply to healthy volunteers or patients with patellofemoral disorders. As this is a preliminary study using cone-beam CT in the upright weight-bearing position, further studies are needed to establish threshold values in a larger population, in healthy volunteers and in patients with specific patellofemoral diseases. Examination of different degrees of knee flexion may help illustrate patellar alignment, mimicking physiological conditions such as walking or climbing stairs.

In conclusion, the knee joint alignment differs significantly in the upright weight-bearing position compared to the supine non-weight-bearing position using CT.

Acknowledgments The scientific guarantor of this publication is Anna Hirschmann, MD. The authors of this manuscript declare no relationships with any companies whose products or services may be related to the subject matter of the article. The authors state that this work has not received any funding. One of the authors has significant statistical expertise; however, no complex statistical methods were necessary for this paper. Institutional Review Board approval was obtained. Written informed consent was obtained from all patients in this study. Methodology: prospective, diagnostic study performed at one institution

References

1. Draper CE, Besier TF, Fredericson M et al (2011) Differences in patellofemoral kinematics between weight-bearing and non-weight-bearing conditions in patients with patellofemoral pain. J Orthop Res 29:312–317
2. Powers CM, Ward SR, Fredericson M, Guillet M, Shellock FG (2003) Patellofemoral kinematics during weight-bearing and non-weight-bearing knee extension in persons with lateral subluxation of the patella: a preliminary study. J Orthop Sports Phys Ther 33: 677–685
3. Souza RB, Draper CE, Fredericson M, Powers CM (2010) Femur rotation and patellofemoral joint kinematics: a weight-bearing magnetic resonance imaging analysis. J Orthop Sports Phys Ther 40:277–285
4. Ward SR, Terk MR, Powers CM (2007) Patella alta: association with patellofemoral alignment and changes in contact area during weight-bearing. J Bone Joint Surg Am 89:1749–1755
5. Pal S, Besier TF, Beaupre GS, Fredericson M, Delp SL, Gold GE (2013) Patellar maltracking is prevalent among patellofemoral pain subjects with patella alta: an upright, weightbearing MRI study. J Orthop Res 31:448–457
6. Gold GE, Besier TF, Draper CE, Asakawa DS, Delp SL, Beaupre GS (2004) Weight-bearing MRI of patellofemoral joint cartilage contact area. J Magn Reson Imaging 20:526–530
7. Powers CM, Shellock FG, Pfaff M (1998) Quantification of patellar tracking using kinematic MRI. J Magn Reson Imaging 8:724–732
8. Doucette SA, Child DD (1996) The effect of open and closed chain exercise and knee joint position on patellar tracking in lateral patellar compression syndrome. J Orthop Sports Phys Ther 23:104–110
9. Tennant S, Williams A, Vedi V, Kinmont C, Gedroyc W, Hunt DM (2001) Patello-femoral tracking in the weight-bearing knee: a study of asymptomatic volunteers utilising dynamic magnetic resonance imaging: a preliminary report. Knee Surg Sports Traumatol Arthrosc 9:155–162
10. Izadpanah K, Weitzel E, Vicari M, et al (2014) Influence of knee flexion angle and weight bearing on the Tibial Tuberosity-Trochlear Groove (TTTG) distance for evaluation of patellofemoral alignment. Knee Surg Sports Traumatol Arthrosc 22(11):2655-2661
11. Tuominen EK, Kankare J, Koskinen SK, Mattila KT (2013) Weight-bearing CT imaging of the lower extremity. AJR Am J Roentgenol 200:146–148
12. Demehri S, Muhit A, Zbijewski W, et al. (2015) Assessment of image quality in soft tissue and bone visualization tasks for a dedicated extremity cone-beam CT system. Eur Radiol. doi:10.1007/s00330-014-3546-6
13. Lin YF, Jan MH, Lin DH, Cheng CK (2008) Different effects of femoral and tibial rotation on the different measurements of patella tilting: an axial computed tomography study. J Orthop Surg Res 3:5
14. Pfirrmann CW, Zanetti M, Romero J, Hodler J (2000) Femoral trochlear dysplasia: MR findings. Radiology 216:858–864
15. Schoettle PB, Zanetti M, Seifert B, Pfirrmann CW, Fucentese SF, Romero J (2006) The tibial tuberosity-trochlear groove distance; a comparative study between CT and MRI scanning. Knee 13:26–31
16. Sasaki T, Yagi T (1986) Subluxation of the patella. Investigation by computerized tomography. Int Orthop 10:115–120
17. Urch SE, Tritle BA, Shelbourne KD, Gray T (2009) Axial linear patellar displacement: a new measurement of patellofemoral congruence. Am J Sports Med 37:970–973
18. Rosner B. Fundamentals of biostatistics, 7th ed. Boston: Brooks/Cole, Cengage Learning, 2011:xvii, 859 p.
19. Dupuy DE, Hangen DH, Zachazewski JE, Boland AL, Palmer W (1997) Kinematic CT of the patellofemoral joint. AJR Am J Roentgenol 169:211–215
20. Hirschmann A, Pfirrmann CW, Klammer G, Espinosa N, Buck FM (2014) Upright cone CT of the hindfoot: comparison of the non-weight-bearing with the upright weight-bearing position. Eur Radiol 24:553–558
21. van Kampen A, Huiskes R (1990) The three-dimensional tracking pattern of the human patella. J Orthop Res 8:372–382
22. Camp CL, Stuart MJ, Krych AJ et al (2013) CT and MRI measurements of tibial tubercle-trochlear groove distances are not equivalent in patients with patellar instability. Am J Sports Med 41:1835–1840
23. Dietrich TJ, Betz M, Pfirrmann CW, Koch PP, Fucentese SF (2014) End-stage extension of the knee and its influence on tibial tuberosity-trochlear groove distance (TTTG) in asymptomatic volunteers. Knee Surg Sports Traumatol Arthrosc 22:214–218
24. 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
25. Koeter S, Diks MJ, Anderson PG, Wymenga AB (2007) A modified tibial tubercle osteotomy for patellar maltracking: results at two years. J Bone Joint Surg (Br) 89:180–185