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Journal Article

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Publication date:
2020-10

Permanent link:
https://doi.org/10.3929/ethz-b-000442892

Originally published in:
The Journal of Arthroplasty 35(10), https://doi.org/10.1016/j.arth.2020.05.039

The Journal of Arthroplasty 35 (2020) 3010–3030

Contents lists available at ScienceDirect

The Journal of Arthroplasty

journal homepage: www.arthroplastyjournal.org

Basic Science

Videofluoroscopic Evaluation of the Influence of a Gradually Reducing Femoral Radius on Joint Kinematics During Daily Activities in Total Knee Arthroplasty

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ARTICLE INFO

Article history:
Received 28 February 2020
Received in revised form
23 April 2020
Accepted 18 May 2020
Available online 27 May 2020

Keywords:
Attune
Sigma
moving fluoroscopy
in vivo kinematics
gait analysis
condylar geometry

ABSTRACT

Background: Paradoxical anterior translation in midflexion is reduced in total knee arthroplasties (TKAs) with a gradually reducing femoral radius, when compared to a 2-radii design. This reduction has been shown in finite element model simulations, in vitro tests, intraoperatively, and recently also in vivo during a lunge and unloaded flexion-extension. However, TKA kinematics are task dependent and this reduction has not been tested for gait activities.

Methods: Thirty good outcome subjects ($\geq$1 year postoperatively) with a unilateral cruciate-retaining TKA with a gradually reducing ($n = 15$) or dual ($n = 15$) femoral radius design were assessed during 5 complete cycles of level walking, stair descent (0.18-m steps), deep knee bend, and sitting down onto and standing up from a chair, using a moving fluoroscope (25 Hz, 1 ms shutter time). Kinematic data were extracted by 2D/3D image registration.

Results: Tibiofemoral ranges of motion for flexion-extension, abduction-adduction, internal-external rotation, and anteroposterior (AP) translation were similar for both groups, whereas the pattern of AP translation-flexion-coupling differed. The subjects with the dual-radii design showed a sudden change in direction of AP translation around 30° of flexion, which was not present in the subjects with the gradually reducing femoral radius design.

Conclusion: Through the unique ability of moving fluoroscopy, the present study confirmed that the gradually reducing femoral radii eliminated the paradoxical sudden anterior translation at 30° present in the dual-radii design in vivo during daily activities, including gait and stair descent.

Total knee arthroplasties (TKAs) aim to relieve patient pain and improve functionality of the joint. To maintain sufficient range of motion (ROM), but also not overload the surrounding soft tissue structures, reproduction of tibiofemoral kinematics of the healthy knee is thought to be beneficial. The movement of the normal tibiofemoral joint has been extensively investigated in cadaver studies [1], using magnetic resonance imaging [2–4] or computed tomography as well as by bone pins [5], radiostereometric analysis [6,7], and videofluoroscopy [8–11]. In contrast to the studies describing the healthy (no significant tibiofemoral arthritis) native knee kinematics as a medial pivot motion [2,4,8,9,11,12], other studies suggest that during the loaded stance phase of gait, the center of rotation of the joint may be predominantly on the lateral side [7,10,13]. It remains unknown whether the loading conditions, the analysis technique, or leg alignment is responsible for this discrepancy between studies. Although normal knee motion is controversially discussed, current TKA geometries are designed with the goal to replicate a medial pivot with a lateral femoral rollback during flexion [12].

In comparison with posterior-stabilized designs, cruciate-retaining (CR) designs showed less total rollback [14] and in some CR designs even a lack of posterior femoral rollback and an average anterior femoral translation with knee flexion [15]. In general, the

One or more of the authors of this paper have disclosed potential or pertinent conflicts of interest, which may include receipt of payment, either direct or indirect, institutional support, or association with an entity in the biomedical field which may be perceived to have potential conflict of interest with this work. For full disclosure statements refer to https://doi.org/10.1016/j.arth.2020.05.039.

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https://doi.org/10.1016/j.arth.2020.05.039
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paradoxical anterior movement of the condyles during flexion was mainly observed in CR designs [16–22]. However, some studies reported a posterior femoral rollback for CR designs as well, which was attributed to the asymmetric design of the femoral condyles [23,24]. Nevertheless, several authors have reported a sudden anterior slide, also referred to as paradoxical anterior translation, of the femoral condyle relative to the tibial component in posterior cruciate ligament–retaining TKAs [17,21,22,25,26].

Reduced paradoxical anterior translation in midflexion has been reported for femoral components with a gradually reducing radius when compared to a 2-radii design, based on finite element model simulations and in vitro tests [25]. Recently, this has also been shown intraoperatively [27], as well as in vivo during a lunge and unloaded flexion-extension [22]. The latter study compared tibiofemoral kinematics of 20 subjects with a dual-radii design (Sigma CR rotating platform TKA, DePuy Synthes) with 10 subjects with a gradually reducing femoral radii design (Attune CR rotating platform TKA, DePuy Synthes) assessed in vivo by means of fluoroscopy at 24 months after surgery. It was shown that the lateral condyle of the subjects with the gradually reducing femoral radii design showed a higher extent of femoral rollback while the lateral condyle of the subjects with the dual-radii design rolled forward during flexion-extension, as well as during the lunge. For the medial condyle, a higher roll-forward was observed in the subjects with the dual-radii design during flexion-extension, whereas movements in both groups were similar for the medial condyle during the lunge. However, TKA kinematics are task dependent, thus are not simply flexion dependent, but rather vary between different loading conditions and activities of daily living [28,29]. Therefore, it needs to be tested whether the reduction of paradoxical anterior translation with a gradually reducing femoral radius can also be confirmed during loaded locomotive activities.

Single plane videofluoroscopic analysis [29–35] as well as dual orthogonal fluoroscopy [36,37] with subsequent 2D/3D registration [31,38] has provided valuable information in the study of 3D motion of TKAs as well as healthy knees. Due to the drawback of a limited field of view of the generally stationary image intensifier, past research very often focused on examining the kinematics of the knee during rising up/down from a chair, step-up/step-down and deep knee bends, or only captured a portion of a complete motion cycle [22,39,40]. However, stair activities are considered to be one of the primary daily activities that cause difficulties and suffering for most subjects afflicted with knee disorders. Due to the larger joint moments [41], as well as higher variability and left-right asymmetries [42] compared to level walking, many TKA subjects develop compensatory movements in order to safely complete the task. To overcome the limitations of a static image intensifier and allow tracking of the knee throughout complete cycles of level walking and stair descent, dynamic systems have been developed [34,43–45].

The objective of the present study is to assess kinematic differences in the 3D implant motion during complete cycles of level gait, stair descent, deep knee bend, sitting down onto a chair, and standing up from a chair, comparing a cohort with a CR, fixed-bearing (FB) TKA with a gradually reducing femoral radius to a cohort with a conventional CR FB TKA with a dual-radii femoral design.

Materials and Methods

Subjects

Fifteen volunteers with a unilateral CR FB TKA with a gradually reducing femoral radius (GRAD) (Attune, DePuy Synthes, Johnson and Johnson) (7 female/8 male; age 69.2 ± 8.6 years; 18.3 ± 3.4 months postoperatively; body mass index [BMI] 27.9 ± 3.4 kg/m^2; Knee Injury and Osteoarthritis Outcome Score [KOOS] 88.5 ± 8.7) and 15 volunteers with a unilateral CR FB TKA with a dual-radii femoral component (DUAL) (Sigma, DePuy Synthes, Johnson and Johnson) (4 female/11 male; age 67.6 ± 9.0 years; 31.8 ± 26.4 months postoperatively; BMI 26.8 ± 3.6 kg/m^2; KOOS 92.0 ± 4.9) participated in this study. GRAD subjects were recruited by the Charité Universitätsmedizin in Berlin, Germany, the Klinikum rechts der Isar in München, Germany, and the Kantonsspital in Olten, Switzerland, whereas DUAL subjects were recruited by the Asana Spital in Leuggern, Switzerland, and Ortho Aarau in Aarau, Switzerland, based on the inclusion and exclusion criteria listed in Table 1.

Consistently over both patient groups, a medial parapatellar approach and a femur first technique were used. All 5 operating and recruiting surgeons had extensive experience with the respective implant design. The rehabilitation regime consisted for both patient groups of full weight-bearing starting day 1 after intervention. Physical therapy consisted of stretching as well as strengthening techniques. All subjects included in the study were good outcome subjects (KOOS > 70, no or very low pain with VAS <2, well-aligned TKA). The patient groups did neither differ in age, BMI, nor KOOS, but the time period between surgery and testing was significantly longer for the DUAL group than the GRAD group.

Each subject signed an informed consent in accordance with the local ethics committee (BASEC-Nr. 2016-01682).

Data Acquisition

The kinematic and kinetic data were assessed synchronously by the moving fluoroscope [43], 8 force plates (Kistler AG, Winterthur, Switzerland), which were fully decoupled from the surrounding floor [46] and by an optoelectronic 3D motion analysis system consisting of 22 infrared cameras (Vicon MX system; Oxford Metrics Group, UK) in the motion analysis lab of the Institute for Biomechanics, ETH Zurich. After familiarization trials with the moving fluoroscope, at least 5 repetitions were assessed for each daily activity, namely level walking (5 force plates fixed in a straight line [46]), stair descending (instrumented 3-step staircase [43]), standing up from a chair, sitting down onto a chair, and deep knee bending (Fig. 1). The moving fluoroscope was used to assess fluoroscopic images of complete gait, respectively motion cycles of the TKA with a measurement frequency of 25 Hz, a shutter time of 1 ms, and an image resolution of 1000 × 1000 pixels. Technical details of the system have been published previously [43].

Table 1
Inclusion and Exclusion Criteria.

Inclusion Criteria
• Unilateral TKA (Attune CR fixed-bearing/Sigma curved CR fixed-bearing) due to OA
• BMI ≤ 33
• Good clinical outcome, KOOS > 70
• No or very low pain VAS < 2
• At least 1 year postop
• Standardized general health survey score (SF-12) within the normal range for people in their age-group
Exclusion Criteria
• Actual significant problem on lower extremities
• Misaligned TKA
• Any other arthroplasty at the lower extremities
• Patient incapable to understand and sign informed consent
• Incapable of performing the motion tasks
• Pregnancy

TKA, total knee arthroplasty; CR, cruciate-retaining; OA, osteoarthritis; BMI, body mass index; KOOS, Knee Injury and Osteoarthritis Outcome Score; VAS, visual analog scale; postop, postoperatively; SF-12, Short Form 12.

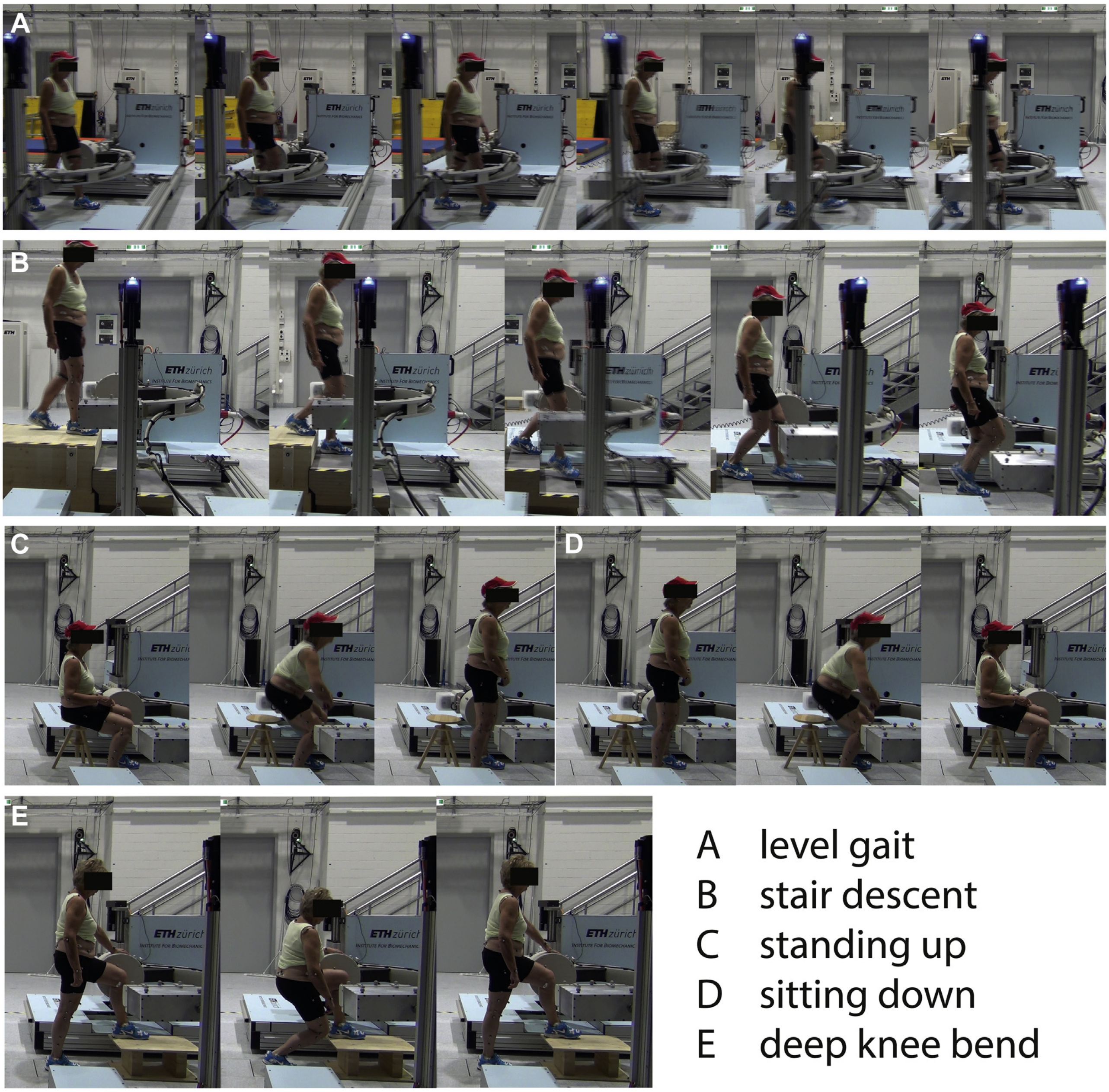

Fig. 1. Subject performing the daily activities within the moving fluoroscope setup.

Data Processing

For level gait and stair descent, a ground reaction force threshold of 25 N was used to determine events defining the gait cycles (underlying ground reaction force measurement frequency of 2000 Hz), including stance and swing phases. For the sitting as well as knee bending tasks, the start and end points of the motion cycles were defined by the vertical velocity of the skin marker mounted on the sternum (velocity >0.02 m/s), with an underlying marker measurement frequency of 100 Hz.

Fluoroscopic images were distortion corrected using a local algorithm operating on a reference grid [32,47]. Projection parameters of the fluoroscopic system (focal distance, location of the principle point in the image plane) were determined by a least-squares optimization using 5 images of a calibration tube [32]. The 3D pose of the TKA components was determined by a 2D/3D registration based on the CAD models of the implant components. The registration algorithm is based on the approach developed by Burckhardt et al [38]. This process has reported registration errors of $\leq$0.25° for all rotations, 0.3 mm for in-plane, and 1.0 mm for out-of-plane translations for the balanSys TKA [32].

The relative rotations between the femoral and tibial components were determined using the joint coordinate system convention by Grood and Suntay [48], based on the femoral and the tibial implant coordinate systems (Fig. 2). Anteroposterior (AP) translation was calculated based on the nearest point analysis (NPA) presented in the tibial coordinate system. Thus, movement of the medial and lateral femoral condyles was described relative to the top plane of the tibial baseplate by using a weighted mean of the 10 nearest points on each condyle. AP translation was normalized to a medium size of the femoral component with a peg distance of 44 mm (normalization factor = 44 mm/peg distance).

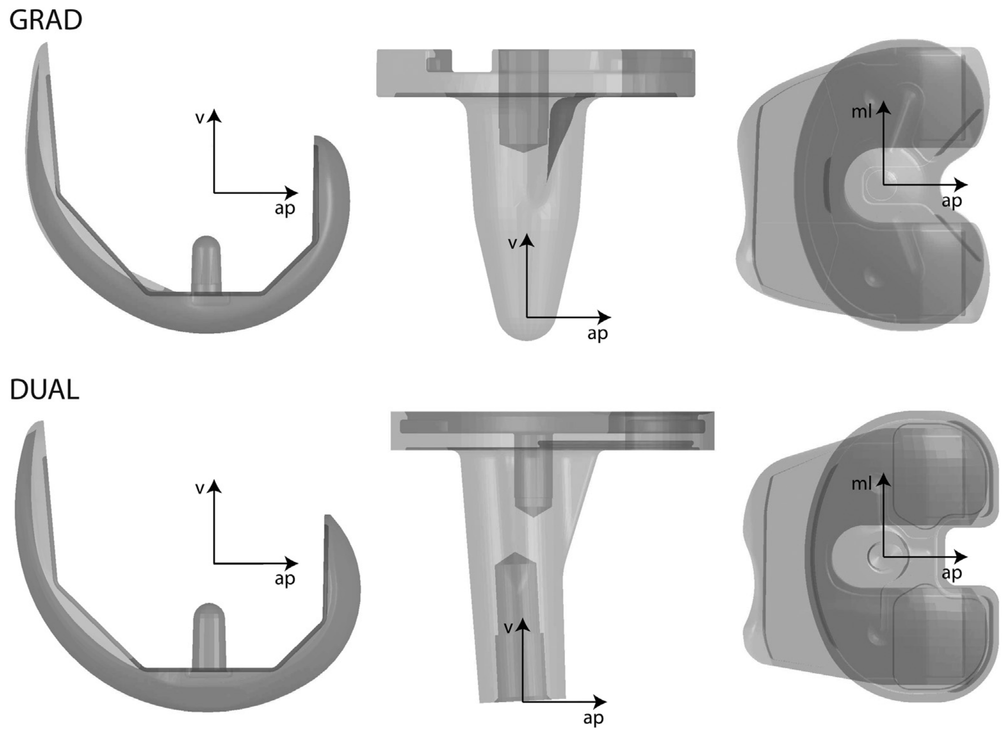

Fig. 2. Implant coordinate system (black arrows) for the femoral and tibial components of the gradually reducing femoral radius (GRAD) and dual-radii femoral component (DUAL) total knee arthroplasty (TKA)—mediolateral (ml) axis, anteroposterior (ap) axis, and vertical (v) axis.

The kinematic outcome parameters included maximal ROMs (ranges between the maximal and minimal reached values occurring during the whole motion cycles) for the sagittal, frontal, and transverse plane rotations as well as for AP translation. For level gait and stair descent, additional ROMs for the loaded stance and unloaded swing phase were evaluated.

Gait velocity, step length, and stance time for level walking were defined based on the ground reaction forces, respectively center of force application.

Statistics

The null hypothesis was defined as no difference between the implant kinematics of the GRAD and the DUAL cohort. By means of a 2-tailed unpaired *t*-test, the kinematic parameters were tested for the group comparison. A Bonferroni correction was applied for post hoc multiple comparisons, considering the analysis of 10 activities (level gait whole cycle, level gait stance, level gait swing, stair descent whole cycle, stair descent stance, stair descent swing, sit to stand, stand to sit, deep knee bend extension, and deep knee bend flexion; significance level adjusted from 0.05 to 0.005). All statistics were conducted in SPSS (SPSS v24, IBM, Armonk, NY).

To enable the statistical analysis of a vector (flexion series) rather than just extracted scalars, an open-source 1D statistical parametric mapping code (SPM) (v0.4, www.spm1d.org) was used to test the effect of implant geometry for entire waveforms of medial and lateral AP translation-flexion-coupling, as well as internal-external rotation-flexion-coupling during level gait, stair descent, and the sit task [49]. Deep knee bend was not included into the SPM analysis because statistical comparison was not feasible due to the varying individual flexion ranges and the unbalanced group sizes, as not all individuals performed this task. SPM with unpaired 2-tailed *t*-tests was used for the comparison of the 2 TKA groups. Additionally, a Bonferroni correction was applied for post hoc multiple comparisons, considering the analysis of 6 activities (level gait stance, level gait swing, stair descent stance, stair descent swing, sit to stand, and stand to sit; significance level adjusted from 0.05 to 0.0083). To allow statistical comparison of an absolute position of AP translation between the 2 implant designs, AP translation at heel strike (HS) of level gait was defined as reference, thus zero AP translation. In other words, for the SPM of the AP translation-flexion-coupling graphs, AP translation graphs were shifted for each individual subject relative to the average AP translation at HS of level gait of each individual subject. SPM analysis is only performed at flexion ranges for which data of each individual subject are available.

Results

ROM for flexion-extension, abduction-adduction, and internal rotation was similar for the GRAD and the DUAL subjects for all tasks (Table 2, Appendix Table B.1). The largest flexion-extension ROM occurred during stair descent, as well as during the 2 sitting tasks. For both TKA geometries, the maximal flexion angle was reached during the deep knee bending task (GRAD: 103.7° ± 14.3°, DUAL: 98.4° ± 11.5°). At the beginning of the deep knee bending task, the average flexion angle was 69.0° ± 11.3° for the GRAD and 66.0° ± 11.9° for the DUAL subjects. After maximal flexion, followed by extension, the deep knee bending task ended in an average position of 61.1° ± 11.4° for the GRAD and 58.9° ± 8.4° for the DUAL subjects.

Both TKA geometries do show internal tibial rotation with increasing flexion, above 30° of flexion (Figs. 3-5, Appendix Figure A.1), and the ROM of internal-external rotation did not significantly differ between the 2 designs for all tasks (Table 2, Appendix Table B.1). The tibial component of the GRAD stayed, on average over all subjects, internally rotated throughout all motion tasks and flexion angles. The orientation of the tibial component of

Table 2
Mean and SD for Sagittal, Frontal, and Transversal Knee Rotations Over All GRAD and All DUAL Subjects (GRAD n = 15, DUAL n = 15 [for DKB: GRAD n = 14, DUAL n = 9]) by Means of Videofluoroscopy.

Task	TKA	Flexion-Extension			Adduction-Abduction			Internal-External Rotation		
		ROM (°)			ROM (°)			ROM (°)		
		Cycle	Stance	Swing	Cycle	Stance	Swing	Cycle	Stance	Swing
Level gait	GRAD	59.3 ± 6.6	34.9 ± 6.4	58.4 ± 6.5	2.7 ± 1.0	2.1 ± 0.6	2.1 ± 0.9	8.0 ± 1.6	6.0 ± 1.3	6.1 ± 1.4
	DUAL	59.5 ± 5.6	33.2 ± 6.9	59.0 ± 5.5	3.0 ± 1.0	1.9 ± 0.5	2.6 ± 1.1	8.0 ± 1.3	5.7 ± 1.0	6.8 ± 1.1
Stair descent	GRAD	89.3 ± 5.2	80.0 ± 6.0	88.9 ± 5.4	3.4 ± 0.7	2.6 ± 0.7	2.5 ± 0.7	9.8 ± 2.3	7.1 ± 2.1	8.8 ± 2.3
	DUAL	85.0 ± 4.9	74.6 ± 5.6	84.3 ± 4.9	2.9 ± 0.6	2.6 ± 0.4	2.0 ± 0.7	8.8 ± 1.9	6.5 ± 1.8	7.5 ± 2.0
Sit to stand	GRAD	83.5 ± 9.4			2.1 ± 0.7			9.1 ± 2.7		
	DUAL	84.3 ± 4.8			1.9 ± 0.8			7.9 ± 2.1		
Stand to sit	GRAD	84.1 ± 11.1			1.8 ± 0.6			7.1 ± 2.7		
	DUAL	85.3 ± 4.3			1.7 ± 0.6			7.0 ± 1.8		
DKB flexion	GRAD	34.8 ± 11.8			2.0 ± 0.8			5.1 ± 1.1		
	DUAL	32.1 ± 12.1			1.5 ± 0.3			4.3 ± 1.5		
DKB extension	GRAD	42.5 ± 11.9			1.8 ± 0.6			4.7 ± 1.1		
	DUAL	39.5 ± 10.9			4.3 ± 1.3			1.4 ± 0.3		

Bonferroni-corrected significance level of $P < .005$.
SD, standard deviation; GRAD, gradually reducing femoral radius; DUAL, dual-radii femoral component; DKB, deep knee bend; TKA, total knee arthroplasty; ROM, range of motion.

the DUAL, however, was on average externally rotated relative to the femoral component for smaller flexion angles. Statistical comparison of tibial rotation at each specific flexion angle between GRAD and DUAL based on an SPM analysis revealed no significant differences during level gait, stair descent, and the sit task (Fig. 5).

The range of AP translation was similar for the GRAD and the DUAL subjects for all tasks and both condyles (Table 3, Appendix Table B.2). For both TKA designs, larger ROM for AP translation was present during the swing than during the stance phase of walking as well as for stair descent (Table 3, Figs. 3 and 4). Although the ROM of flexion-extension from the sitting tasks was comparable to the ROM of flexion-extension during stair descent, both TKAs showed larger ROM of AP translation during stair descent in comparison with the sitting tasks for both condyles (Tables 2 and 3).

Considering the coupling characteristics between AP translation and flexion, on average across all GRAD and all DUAL subjects, neither implant shows a linear relationship over the whole flexion range and for all motion tasks (Appendix Figure A.2). Moreover, the direction of translation that is coupled with flexion is not consistent over the whole flexion range. For certain flexion ranges (mainly lower flexion ranges), tibiofemoral flexion is coupled to anterior translation, whereas for other flexion ranges (mainly higher flexion ranges) tibiofemoral flexion is coupled with a posterior translation. The AP translation-flexion-coupling is furthermore dependent on the task, and mainly on the loading condition. This leads to a different AP translation for a specific flexion angle when comparing the loaded stance to the unloaded swing phase. Average AP translation-flexion-coupling showed a different characteristic when qualitatively comparing coupling graphs of DUAL and GRAD (Fig. 6, Appendix Figure A.2). The most obvious difference is a sudden change in direction from a posterior to an anterior AP translation around 30° of flexion for DUAL, which was not present in the GRAD. The medial condyle of the GRAD showed an anterior translation with increasing flexion, except for part of the swing phases of level gait and stair descent as well as during the deep knee bend for flexion ranges above 80°. The swing phases showed a posterior translation in the medial compartment with increasing flexion for larger flexion ranges. During the deep knee bend, an approximately constant AP position was found for the GRAD. The lateral condyle of the GRAD showed a slight posterior translation with increasing flexion, except for smaller flexion ranges of level gait as well as stair descent. The medial condyle of the DUAL showed roughly constant AP translation below 30°, a local minimum at about 30° followed by an anterior translation with increasing flexion. The lateral condyle of the DUAL showed over the whole flexion range rather a constant position of AP translation, whereas the local minimum at about 30° was also present for the sitting tasks as well as the stance phase of stair descent. Statistical comparison of AP translation at each specific flexion angle between GRAD and DUAL based on an SPM analysis revealed a significant difference in the waveform of AP translation-flexion-coupling for the medial condyle during the swing phase of level gait for the range of 24° to 41° flexion (Fig. 6). The qualitative analysis of the AP translation-flexion coupling pattern of each individual subject revealed that the local minima observed at about 30° flexion was seen in all 15 DUAL subjects, but none of the GRAD subjects (Appendix Figures A.3-A.8).

It is worth mentioning that the gait characteristics of the GRAD and the DUAL subjects did not differ in terms of gait velocity (GRAD: 0.85 ± 0.06 m/s, DUAL: 0.84 ± 0.06 m/s), stance time (GRAD: 0.92 ± 0.09 s, DUAL: 0.95 ± 0.11 s), and step length (GRAD: 0.55 ± 0.04 m, DUAL: 0.56 ± 0.04 m).

Discussion

To improve functionality and quality of life, TKAs aim to relieve pain and restore function of the knee joint throughout activities of daily living. Thereby, TKAs try to replicate the motion of the normal healthy joint to allow surrounding soft tissues to maintain their physiological function. Previous studies have shown that tibiofemoral kinematics are task dependent, thus are not simply flexion dependent, but vary between different activities of daily living and especially between loaded and unloaded phases [28,29,50,51]. For this reason, the kinematics of the GRAD and the DUAL were evaluated for several consecutive cycles of functional activities including stance and swing phases.

A preliminary understanding of the effectiveness of a gradually reducing radius to reduce paradoxical anterior translation and improve femoral rollback has been provided in experimental and cadaveric studies [25], as well as intraoperatively [27] and in vivo during a lunge and unloaded flexion-extension [22]. With this study, the in vivo kinematics of the GRAD have now been analyzed for the first time during level walking, stair descent, a sitting, and a deep knee bending activity. Using a unique moving fluoroscope [43], the accurate assessment of tibiofemoral implant kinematics throughout complete gait cycles without errors due to skin movement artifacts [5,52] was possible. The additional comparison against the conventional dual-radius design DUAL using the same

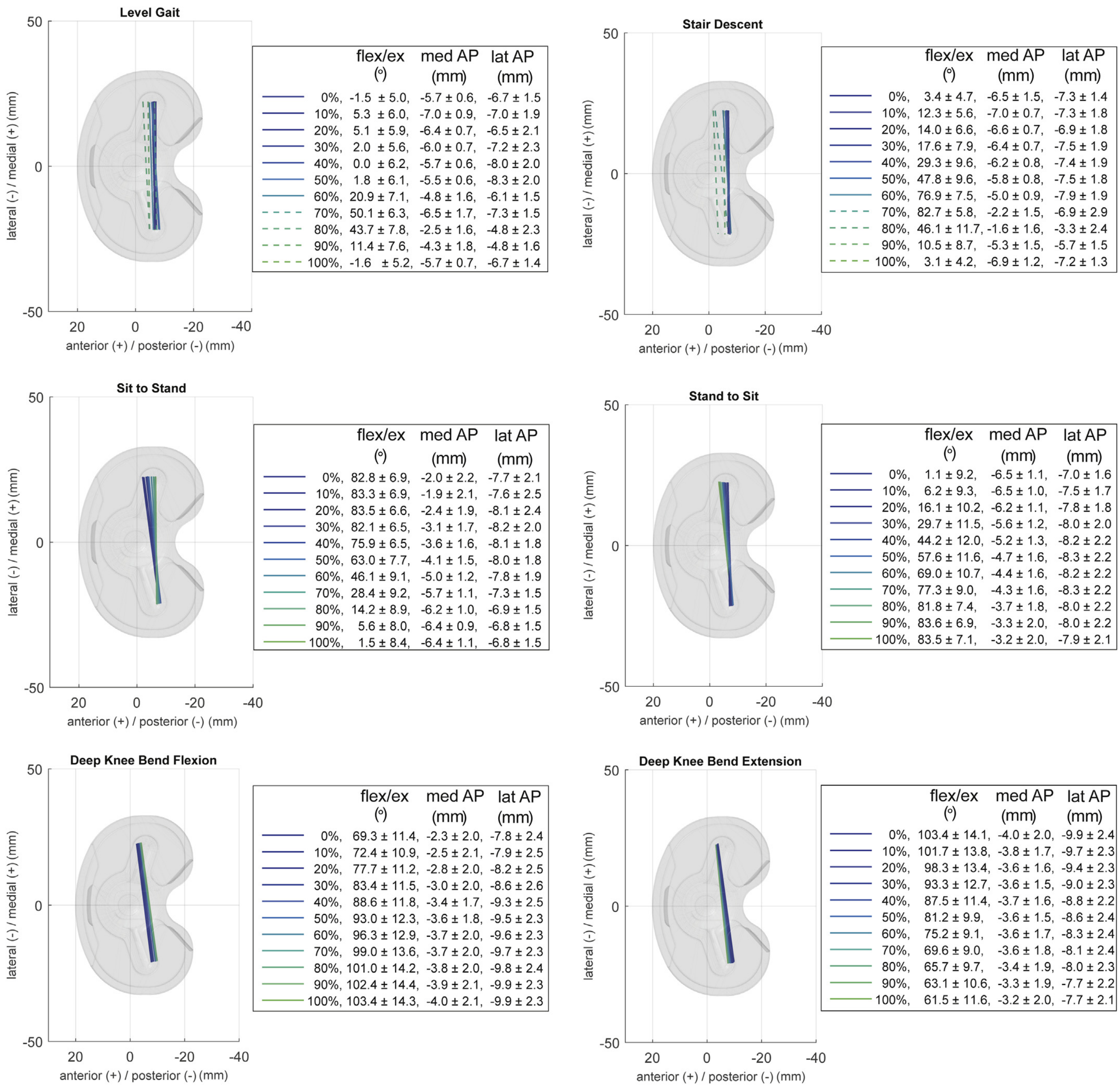

Fig. 3. Average positions of the femoral component of the gradually reducing femoral radius (GRAD) subjects, represented by lines connecting the nearest points of the medial and lateral condyles relative to the tibial tray for specific time points during the motion cycles of the activities. For the gait activities (top row), solid lines represent the loaded stance phase and dotted lines the unloaded swing phase. Mean and standard deviation (SD) of flexion-extension (flex/ex) as well as the anteroposterior (AP) translation of the medial (med) and lateral (lat) condyles across the subject groups for the selected time points are also presented.

measurement setup demonstrated that implant design and even subtle changes in a femoral radius are crucial in driving tibiofemoral kinematics.

In general, tibiofemoral translations and rotations showed highly repeatable individual motion patterns, indicating small variability between trials within each subject, but large intersubject differences were observed, especially for tibial rotation and tibiofemoral translations (Appendix Figures A.3-A.8). We clearly observed subject-specific movement patterns across the different activities, which were considerably larger than any of the intrasubject differences measured between trials. Such differences between subjects indicate that individual anatomic characteristics, including soft tissue tension [53], component implantation [54], limb alignment [55], and muscular activity among others, may all play an important role in governing the subject-specific motion patterns.

Both TKA designs presented a clear characteristic motion pattern for sagittal plane rotation during the gait tasks. It was consistent over all subjects and comparable to previous skin marker studies [56–59], as well as bone pin [60] and fluoroscopy studies [8] of healthy knees. The ROM of tibial rotation determined during the loaded stance phase of level walking (GRAD: 6.0° ± 1.3°, DUAL:

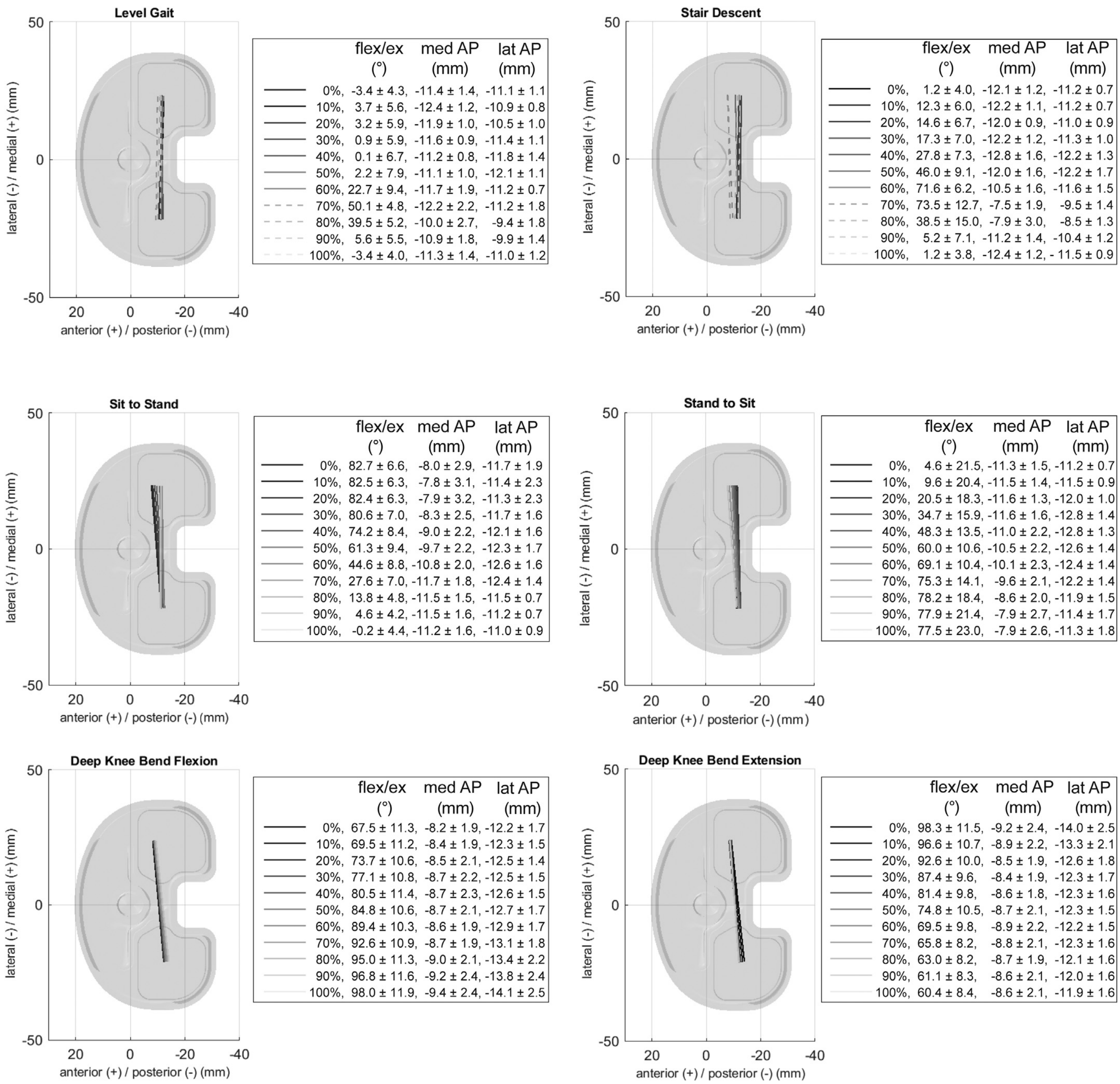

Fig. 4. Average positions of the femoral component of the dual-radii femoral component (DUAL) subjects, represented by lines connecting the nearest points of the medial and lateral condyles relative to the tibial tray for specific time points during the motion cycles of the activities. For the gait activities (top row), solid lines represent the loaded stance phase and dotted lines the unloaded swing phase. Mean and standard deviation (SD) of flexion-extension (flex/ex) as well as the anteroposterior (AP) translation of the medial (med) and lateral (lat) condyles across the subject groups for the selected time points are also presented.

5.7° ± 1.0°) and stair descent (GRAD: 7.1° ± 2.1°, DUAL: 6.5° ± 1.8°) were also comparable to studies investigating the healthy knee in vivo during the stance phase of normal gait and stair descent [5,8,60]. Furthermore, a larger range of tibial rotation was observed during the unloaded swing phase in comparison with the loaded stance phase, which is in agreement with the bone pin study of Lafortune et al [60] looking at healthy knee kinematics. Moreover, the range of tibial rotation occurring during the stance phase of level gait was also comparable to the videofluoroscopy studies of Banks and Hodge [28] assessing 5 different implant designs, as well as of Schmidt et al [61] looking at 3 different implant designs.

For both TKAs, the range of AP translation during the stance phase of level gait (medial: GRAD: 3.7 ± 1.2 mm, DUAL: 3.2 ± 0.8 mm; lateral: GRAD: 3.7 ± 1.0 mm, DUAL: 3.2 ± 0.5 mm) and stair descent (medial: GRAD: 3.9 ± 0.9 mm, DUAL: 4.1 ± 1.2 mm; lateral: GRAD: 3.7 ± 1.1 mm, DUAL: 3.8 ± 0.8 mm) was similar for the medial and lateral condyles. This is not in agreement with the kinematics of the healthy knee, for which Dennis et al [11] as well as Komistek et al [8] have presented a larger AP translation for the lateral condyle than for the medial condyle (lateral: level walking: 7.3 mm and 4.3 mm, stair descent: 3.9 mm; medial: level walking: 0.8 mm and 0.9 mm, stair descent: 2.0 mm). However, a

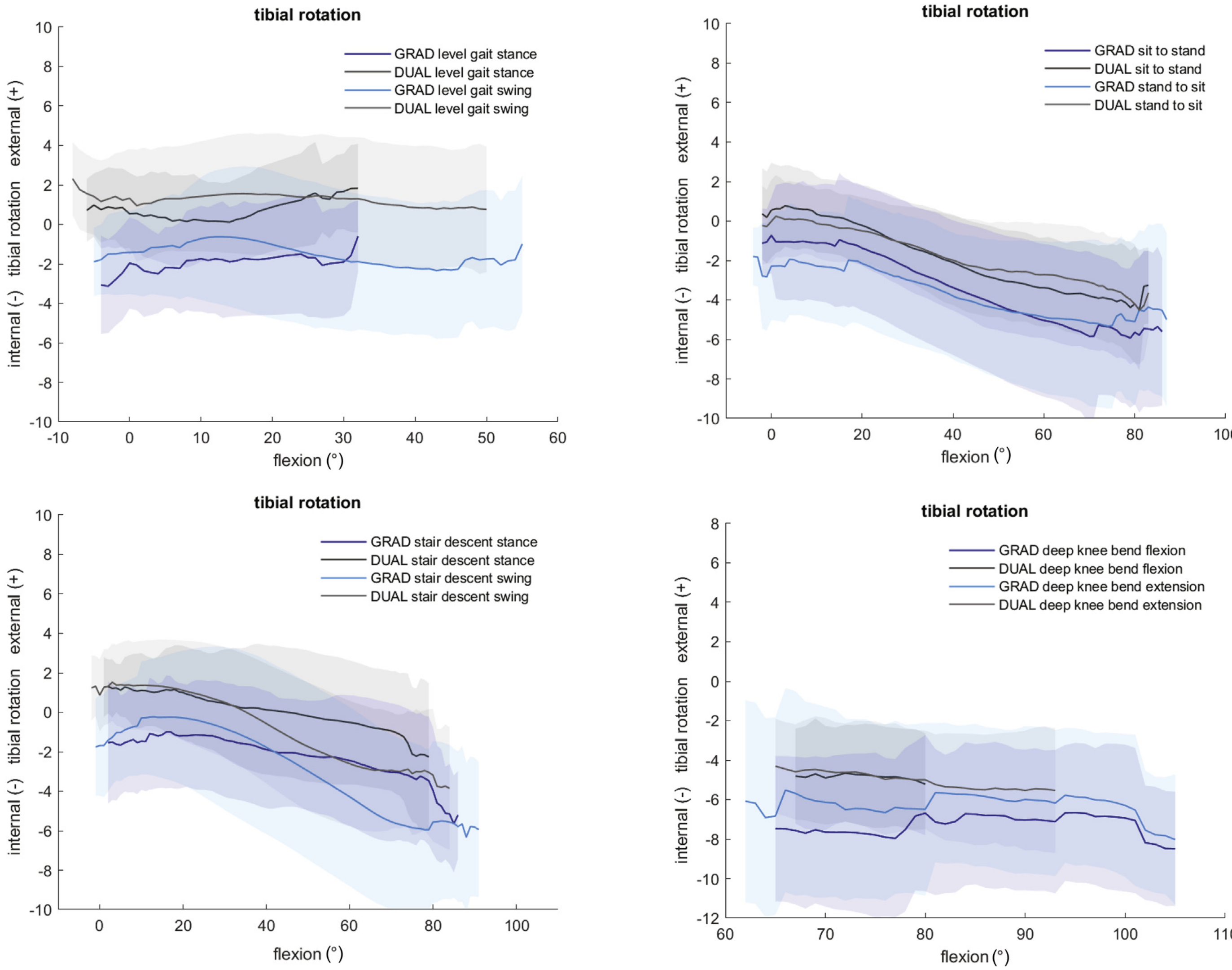

Fig. 5. Comparison of tibial rotation-flexion-coupling between gradually reducing femoral radius (GRAD) and dual-radii femoral component (DUAL) subjects for level gait (top row left), stair descent (bottom row left), sit task (top row right), and deep knee bend (bottom row right). The shaded areas represent the standard deviation (SD) for tibial rotation. Data were only averaged at flexion angles for which at least data of 6 subjects were available. Statistical comparison between GRAD and DUAL is based on statistical parametric mapping (SPM) analysis and an adjusted significance level of $P < .017$. Flexion ranges tested for significance: level gait stance: 9°-18°, level gait swing: 9°-47°, stair descent stance: 13°-71°, stair descent swing: 11°-75°, sit to stand: 19°-72°, stand to sit: 19°-76°. Deep knee bend was not included in SPM analysis.

comparison of these kinematic results against AP translations of healthy knees during gait remains extremely difficult, primarily because normal knee kinematics themselves remain controversially discussed [8,10,11].

For the DUAL CR implant, Schmidt et al [61] reported a smaller AP translation range of the medial condyle (−5.4 mm at HS to −6.7 mm at 33% stance phase) but slightly larger translation on the lateral side (−3.8 mm at HS to −7.8 mm at toe off) for discrete time points during the stance phase of walking, compared to the present study. For the sitting tasks, a slightly larger range of AP translation for the medial and lateral condyle of the DUAL was found in the present study (medial: sit to stand: 6.1 ± 1.8 mm, stand to sit: 5.6 ± 1.4 mm; lateral: sit to stand: 4.6 ± 1.4 mm, stand to sit: 4.2 ± 0.9 mm) compared to a deep knee bending task performed from 0° flexion up to 90° flexion performed with a DUAL implant in the study of Yoshiya et al (medial: −4.7 mm at 0°, −5.9 mm at 30°, −2.1 mm at 60°, −3.2 mm at 90°; lateral: −4.3 mm at 0°, −5.9 mm at 30°, −3.6 mm at 60°, and −5.2 mm at 90°) [20].

For the GRAD, comparable in vivo data are only available from the study of Pfitzner et al [22], in which the medial condyle translated anteriorly by 1.8 ± 1.6 mm from 0° to 70° of flexion during the loaded lunge, whereas the lateral condyle moved posteriorly by −3.9 ± 2.0 mm from 0° to 70° of flexion. This is in agreement with the AP translation of the present study during the sitting tasks for the medial condyle, which also translated anteriorly in a similar manner and range from 0° to 70° of flexion (medial: sit to stand: −6.1 ± 0.9 mm at 0° flexion, −4.8 ± 1.3 mm at 70° flexion; stand to sit: −6.0 ± 0.7 mm at 0° flexion, −5.0 ± 1.4 mm at 70° flexion). For the lateral condyle, the condyle moves posteriorly from 0° to 70° of flexion, consistent with the findings of Pfitzner et al, but the range of posterior translation of the present study (lateral: sit to stand: −6.6 ± 0.8 mm at 0° flexion, −8.1 ± 1.9 mm at 70° flexion; stand to sit: −7.8 ± 2.0 mm at 0° flexion, −8.4 ± 2.2 mm at 70° flexion) is smaller than what has been presented previously.

Neither the GRAD nor the DUAL showed a linear AP translation-flexion-coupling over the whole flexion range. Furthermore, for the medial as well as the lateral condyle, the direction of translation occurring with increasing flexion was not consistent over the whole flexion range. The AP translation-flexion-coupling was dependent on the task for both implants, and mainly on the loading condition.

Table 3
Mean and SD for Medial and Lateral AP Translation Over All GRAD and All DUAL Subjects (GRAD n = 15, DUAL n = 15 [for DKB: GRAD n = 14, DUAL n = 9]) by Means of Videofluoroscopy Based on the Nearest Point Analysis.

Task	TKA	AP Translation					
		ROM (mm)					
		Medial			Lateral		
		Cycle	Stance	Swing	Cycle	Stance	Swing
Level gait	GRAD	6.9 ± 1.7	3.7 ± 1.2	6.2 ± 1.8	6.3 ± 1.8	3.7 ± 1.0	5.0 ± 2.1
	DUAL	6.3 ± 1.8	3.2 ± 0.8	6.0 ± 1.8	5.5 ± 1.2	3.2 ± 0.5	5.0 ± 1.4
Stair descent	GRAD	8.2 ± 1.7	3.9 ± 0.9	7.2 ± 1.8	7.3 ± 2.2	3.7 ± 1.1	6.8 ± 2.4
	DUAL	8.2 ± 2.1	4.1 ± 1.2	7.2 ± 2.0	6.5 ± 1.4	3.8 ± 0.8	5.3 ± 1.2
Sit to stand	GRAD	5.8 ± 2.1			3.5 ± 1.0		
	DUAL	6.1 ± 1.8			4.6 ± 1.4		
Stand to sit	GRAD	4.4 ± 1.7			3.2 ± 1.0		
	DUAL	5.6 ± 1.4			4.2 ± 0.9		
DKB flexion	GRAD	3.6 ± 1.8			3.6 ± 1.5		
	DUAL	2.8 ± 0.8			3.5 ± 1.8		
DKB extension	GRAD	2.7 ± 1.0			3.3 ± 0.9		
	DUAL	2.9 ± 1.0			3.4 ± 1.6		

Bonferroni-corrected significance level of $P < .005$.
SD, standard deviation; AP, anteroposterior; GRAD, gradually reducing femoral radius; DUAL, dual-radii femoral component; DKB, deep knee bend; TKA, total knee arthroplasty; ROM, range of motion.

This is leading to a different AP translation for a specific flexion angle when comparing the loaded stance to the unloaded swing phase. Thus, the resulting AP translation cannot be explained by the flexion angle alone, but is also driven by changes in loading conditions, flexion-extension movement direction, and of course muscle activity. It follows that these differences between the loaded stance and unloaded swing phases indicate the importance of analyzing complete gait cycles.

For the GRAD, the AP translation-flexion-coupling seems to show a different behavior during the gait activities in comparison with the sitting and the knee bending activities. While the gait activity showed on average an anterior translation with increasing flexion for both condyles at lower flexion angles and a posterior translation with increasing flexion at higher flexion angles, this pattern was not observed during the sitting and the knee bending activities. During the sitting and knee bending activities, the GRAD showed on average over all subjects very little translation mainly directed anteriorly with increasing flexion on the medial side (except for larger flexion angles during the deep knee bend). On the lateral side, the GRAD showed a posterior translation with increasing flexion. This femoral rollback of the lateral condyle occurring during the sit and the knee bending tasks, as well as during the gait tasks above 30° of flexion of the GRAD subjects, is in agreement with a previous computational study. It has stated that the gradually reducing femoral sagittal radius of curvature attenuated the anterior slide of the medial femoral condyle and led to a gradual posterior translation of the lateral condyle with knee flexion [62]. Furthermore, our finding is in agreement with the study of Pfitzner et al [22], who recently presented tibiofemoral videofluoroscopy-assessed data of 20 GRAD subjects. During a loaded lunge and unloaded flexion extension movement, they reported a significantly different translation in comparison with the conventional TKA group (CR, conventional femoral changing radius) with an increased lateral rollback above 60° of knee flexion. Pfitzner et al [22] have furthermore found that the GRAD eliminated the medial roll-forward above 80°, whereas for the conventional TKA the lateral condyle rolled forward during the unloaded flexion-extension motion. Qualitatively, this trend can also be seen during our deep knee bending task, but an SPM analysis was not possible due to unbalanced group sizes during the deep knee bending task and the large intersubject variability in the flexion ranges being used to perform the deep knee bending task.

The DUAL shows a local minimum of AP translation at 30° of flexion which is in agreement with previous studies [22,25,27] and plausibly corresponds with the dual-radii design, respectively the abrupt change in femoral radius. The feature was less prominent during unloaded phases, which can be explained by the reduced impact of kinematic guidance by the geometry of the TKA in an unloaded condition. Although the average motion characteristics of the AP translation-flexion-coupling qualitatively shows a different behavior for the DUAL in comparison with the GRAD around 30° of flexion during the stair descent and the sitting activity, no significant differences were found. This can on the one hand be explained by the large interindividual differences in movement pattern as well as timing of motion, but also the restriction that the SPM analysis of the coupling characteristics can only be performed within a balanced design, which means only for the range of flexion angles covered by each individual subject. The characteristic of a sudden change in AP translation around 30° of flexion only significantly differed between the implant designs for the medial condyle during the swing phase of level gait for the flexion range of 23° to 41°. Due to the large variation between subject kinematics, AP translation-flexion-coupling characteristics were also investigated for each individual subject. Thereby, the local minima observed at about 30° flexion was seen in all 15 DUAL subjects and none of the GRAD subjects did show this characteristic of a sudden change in AP translation (Appendix Figures A.3-A.8). It can be followed that the gradually reducing femoral radius eliminated the paradoxical sudden anterior translation at 30° present in the dual-radii design. This finding is in contrast to a previous cadaver study, comparing single-radius and multiradius TKAs with each other and to normal knee motion [63]. In the cadaver study, the implants did not show significant differences in AP translation during the whole ROM of the knee flexion; however, differences were found between both TKAs and the intact knee, although both TKAs followed the intact knee in AP motion within ±2.1 mm in average [63]. Based on these experiments, Stoddard et al [63] further concluded that midrange instability is not related to the shape of the femoral component. This is in contrast to our findings that have shown that the change in femoral radius from a dual-radii design to a gradually reducing radius eliminated the sudden inversion of AP translation at 30° of flexion. In some subjects, this might be related to a midflexion instability. However, the present study only involves good

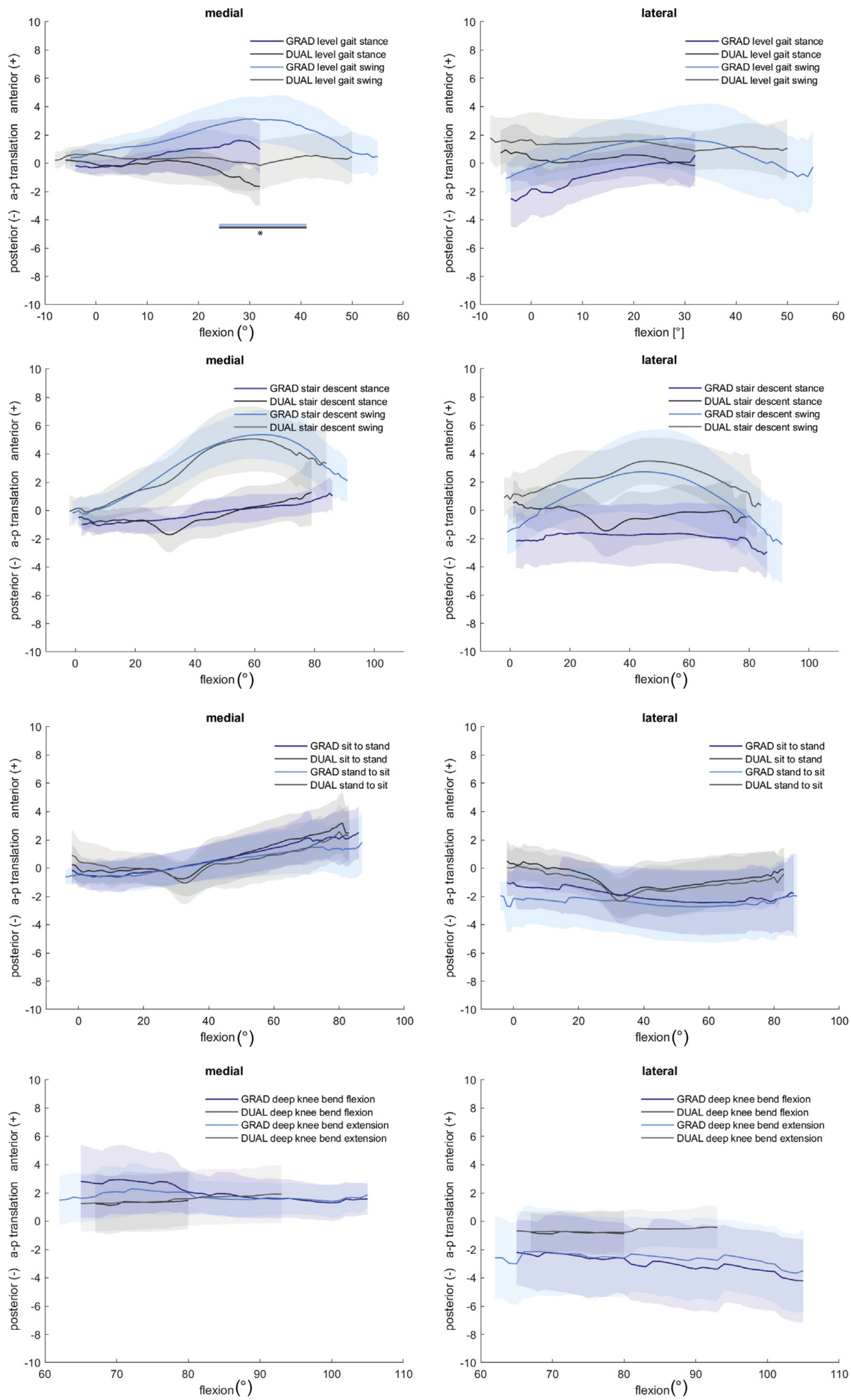

Fig. 6. Comparison of AP translation-flexion-coupling between gradually reducing femoral radius (GRAD) and dual-radii femoral component (DUAL) subjects for level gait (top row), stair descent (second row), sit task (third row), and deep knee bend (bottom row). The shaded areas represent the standard deviation (SD) for anteroposterior (AP) translation. Data were only averaged at flexion angles for which at least data of 6 subjects were available. Zero AP translation reflects AP location at heel strike of level gait of each individual subject. *Statistical difference between GRAD and DUAL is based on statistical parametric mapping (SPM) analysis and an adjusted significance level of $P < .0083$. Flexion ranges tested for significance: level gait stance: 9°-18°, level gait swing: 9°-47°, stair descent stance: 13°-71°, stair descent swing: 11°-75°, sit to stand: 19°-72°, stand to sit: 19°-76°. Deep knee bend was not included in SPM analysis.

outcome subjects and none of them was reporting a feeling of midflexion instability. Therefore, based on the present dataset, it is not feasible to make a conclusion on the correlation between AP translation magnitude and instability feeling. Furthermore, the latter might strongly be influenced by the subjective perception of the individual. Further investigations including instable TKA subjects would be needed to get a better understanding of the relationship between kinematic motion patterns and instability feeling.

AP translation is dependent on the methodology. Thus, AP translation strongly differs in ROM as well as motion pattern when calculated based on a geometric center axis instead of an NPA convention, which was chosen for the present paper. It follows that methodological differences in AP translation should be taken into account when comparing AP translations between different studies. In multiradius designs, the geometric center axis is not always congruent with the actual instantaneous axis of rotation, leading to cross talk between flexion and AP translation for the choice of the geometric center axis approach. And because the amount of cross talk and following resulting AP translation based on a geometric center axis approach is very sensitive to radius changes in the femoral component, the comparison between the 2 implant designs was based on the NPA. However, it is important to be aware that also with the NPA, a change in location of the nearest points should not be interpreted as a pure translation of the implant.

The shift between the AP position of the GRAD and the DUAL subjects is due to the differences in relative position of the origin of the femoral coordinate system relative to the origin of the tibial coordinate system, located at the lowest center point of the stem. It is difficult to make the relation to the lowest points of the polyethylene inlays, which is often used as origin, respectively zero AP position in modeling studies, because the polyethylene inlay is not visible in the fluoroscopic images.

Limitations of the present study are the modest sample size, especially due to the large interindividual differences and the possibility that the moving fluoroscope influences the gait patterns of the subjects. However, in a previous study, it has been shown that walking with the moving fluoroscope limits kinematics in gait velocity, but the kinematics as well as ground reaction forces are comparable to slow walking [57]. Furthermore, the kinematic evaluation based on single plane fluoroscopy with subsequent 2D/3D registration is known to be subject to relatively large out-of-plane errors [32,43,47], which is also the reason why mediolateral translations were not reported. Because the study is not a randomized, blinded design, a variety of influencing factors, such as preoperative ROM, preoperative leg alignment, preoperative conditions of the ligaments, and level of activity, were not controlled.

Conclusions

The present data confirm that the gradually reducing femoral radii eliminated the paradoxical sudden anterior translation at 30° present in the dual-radii design in vivo during daily activities, including gait. The gradually reducing femoral radii improved lateral femoral rollback during the sit tasks as well as above 30° also for the gait activities.

Acknowledgments

This work was financially supported by a research grant from DePuy Synthes (Johnson & Johnson, United States). The authors would like to thank all the subjects who took part in this study, Dr C. Cerletti, Dr R. Gruenig and Prof. Dr C. Perka for their help in patient recruitment and all the students who helped with the measurements and post-processing.

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Appendix A

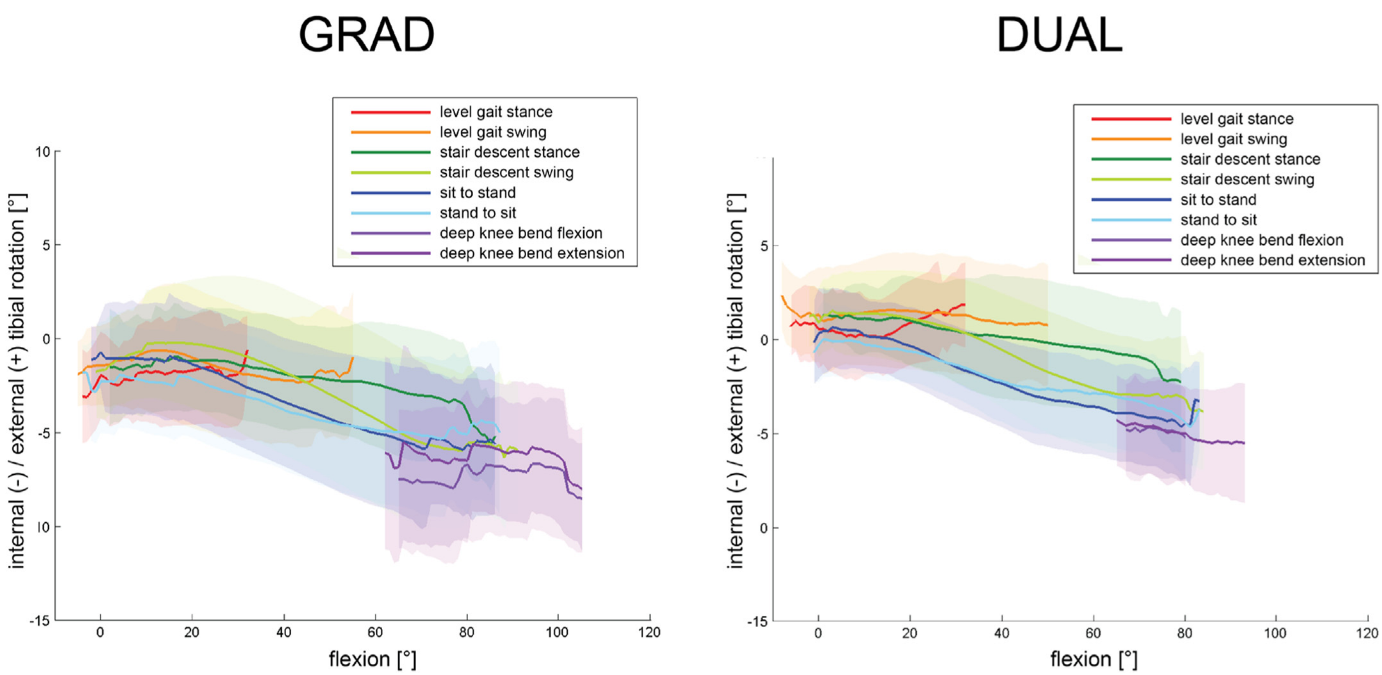

Figure A.1. Tibial rotation-flexion-coupling. Mean across all GRAD (left) and DUAL (right) subjects. The transparent areas represent the SD for tibial rotation across all subjects. Data were only averaged at flexion angles for which at least data of 6 subjects were available. SD, standard deviation; GRAD, gradually reducing femoral radius; DUAL, dual-radii femoral component.

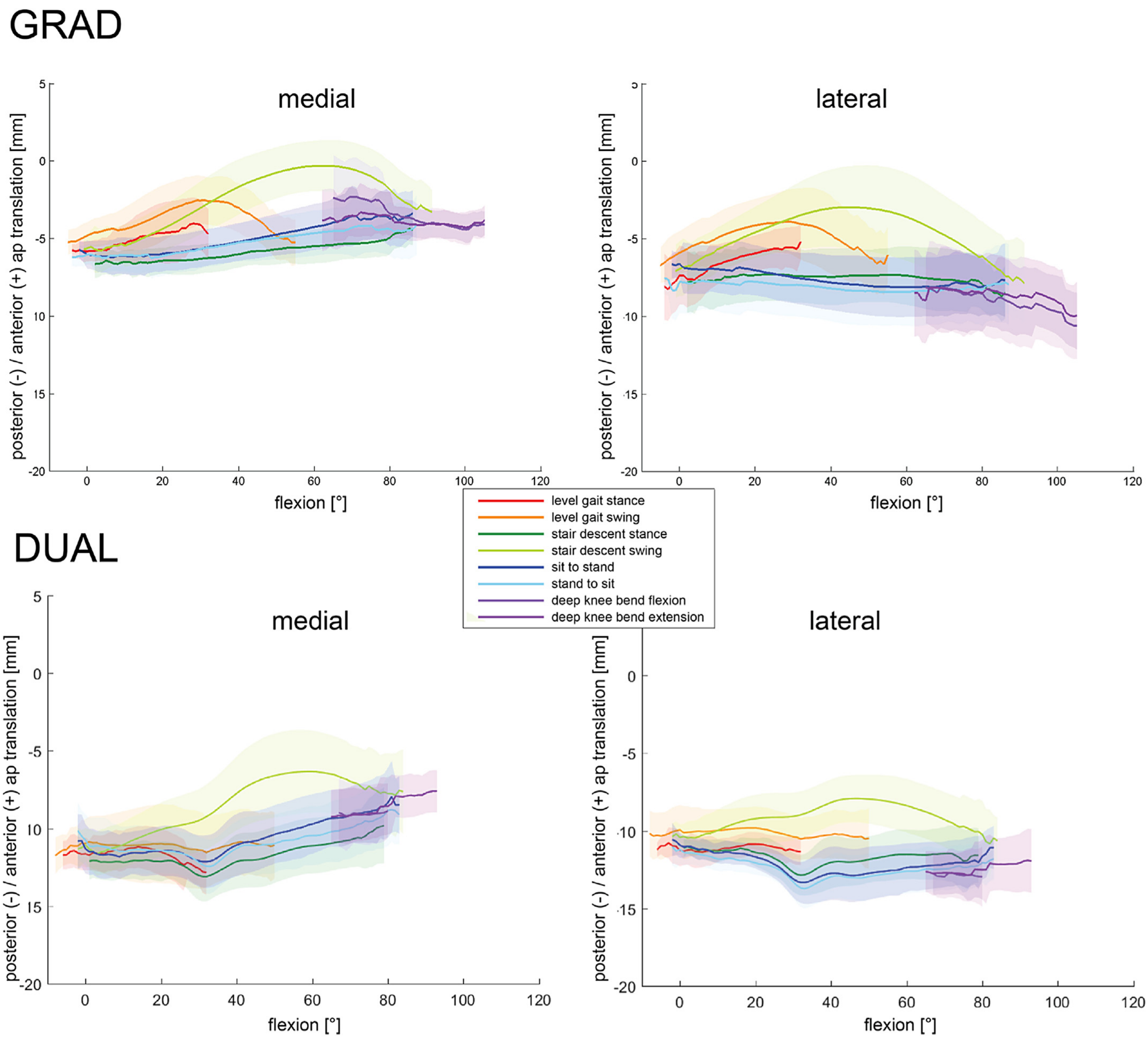

Figure A.2. AP translation-flexion-coupling for the medial and the lateral condyles. Mean across all GRAD (top row) and DUAL (bottom row) subjects. The transparent areas represent the SD for AP translation across all subjects. Data were only averaged at flexion angles for which at least data of 6 subjects were available. AP, anteroposterior.

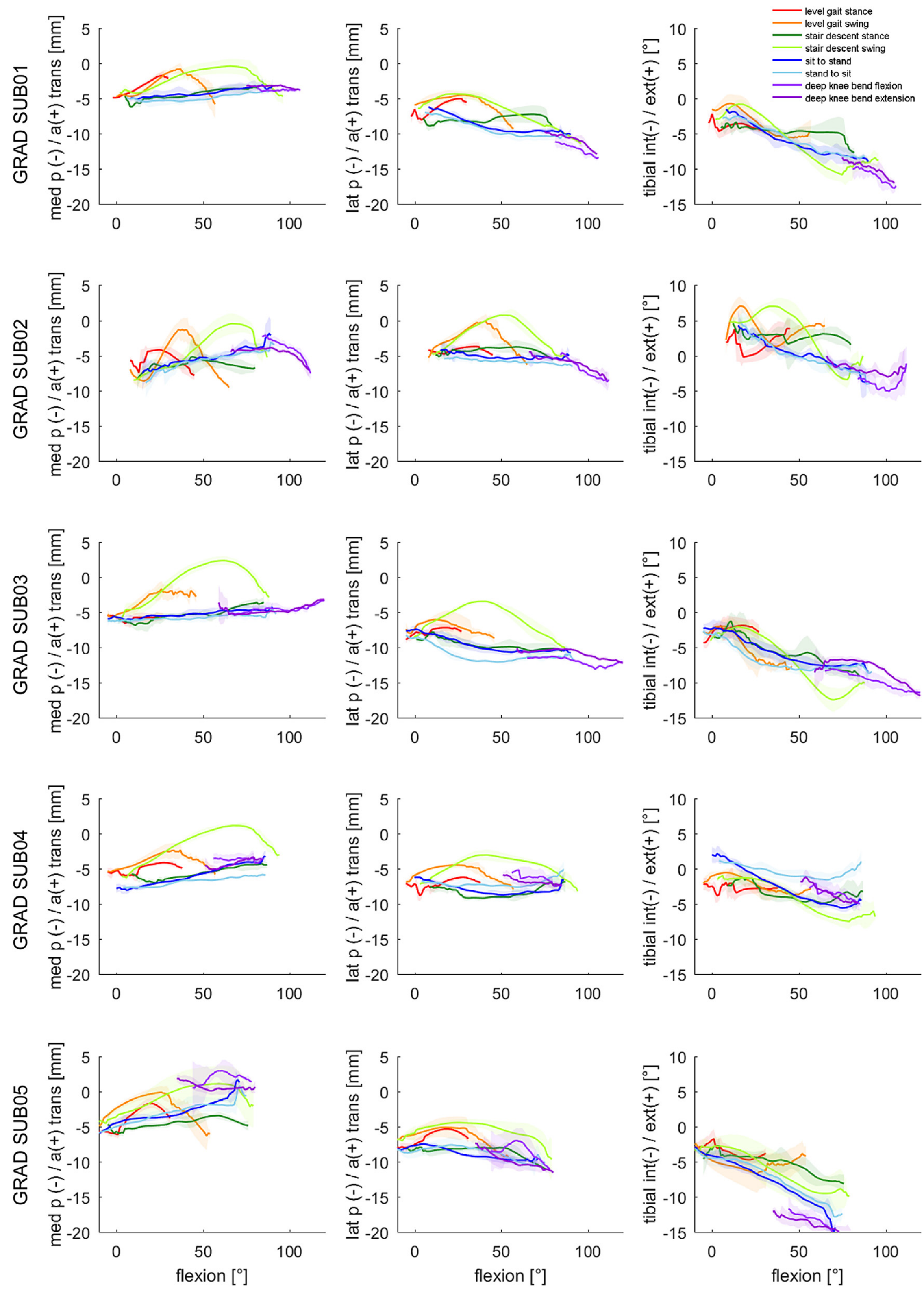

Figure A.3. AP translation-flexion-coupling and tibial rotation-flexion-coupling. Mean over all trials of GRAD subjects SUB01 to SUB05. The shaded areas represent the SD for AP translation over all trials. Data were only averaged at flexion angles for which at least data of 3 trials were available. med, medial; lat, lateral; a, anterior; p, posterior; int, internal; ext, external.

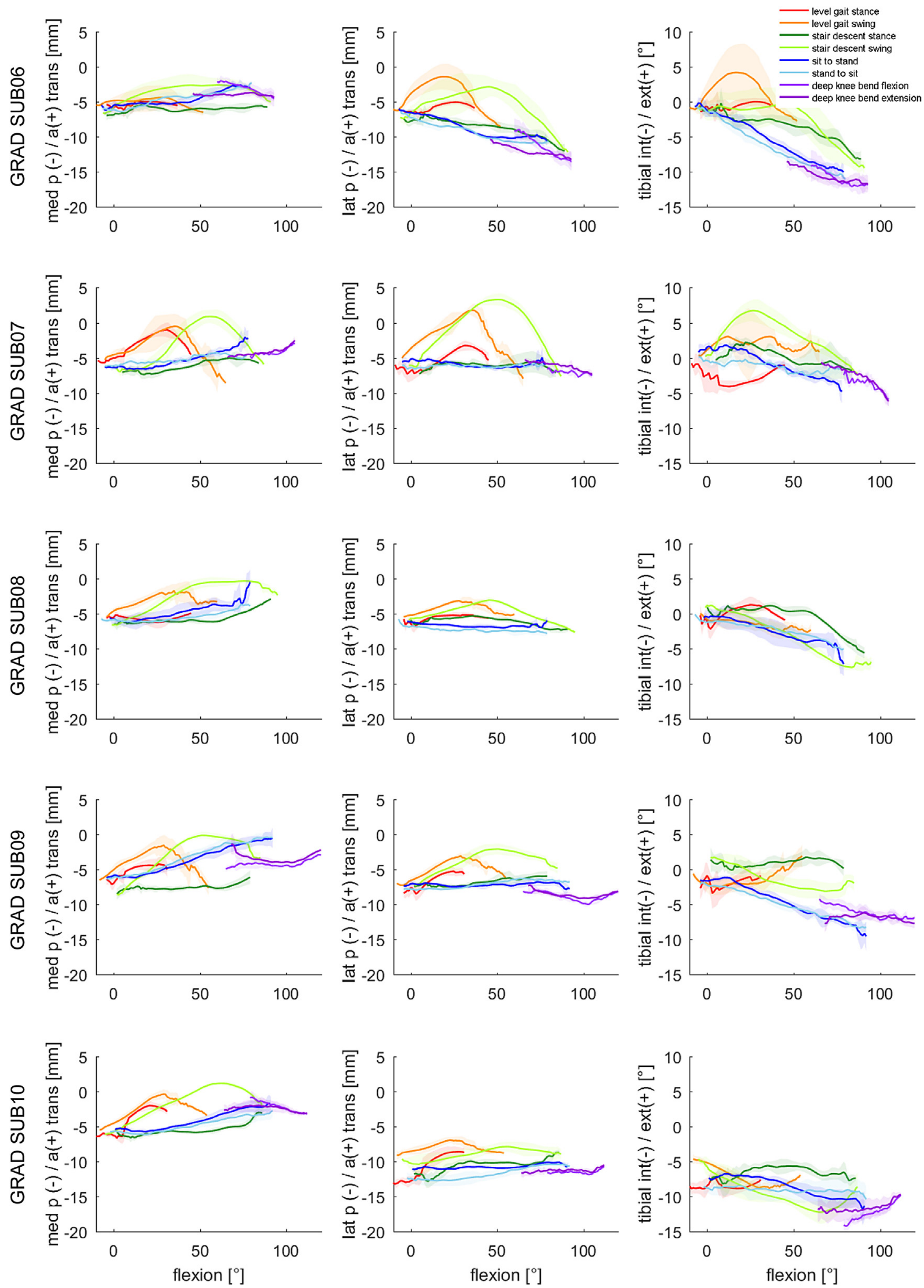

Figure A.4. AP translation-flexion-coupling and tibial rotation-flexion-coupling. Mean over all trials of GRAD subjects SUB06 to SUB10. The shaded areas represent the SD for AP translation over all trials. Data were only averaged at flexion angles for which at least data of 3 trials were available.

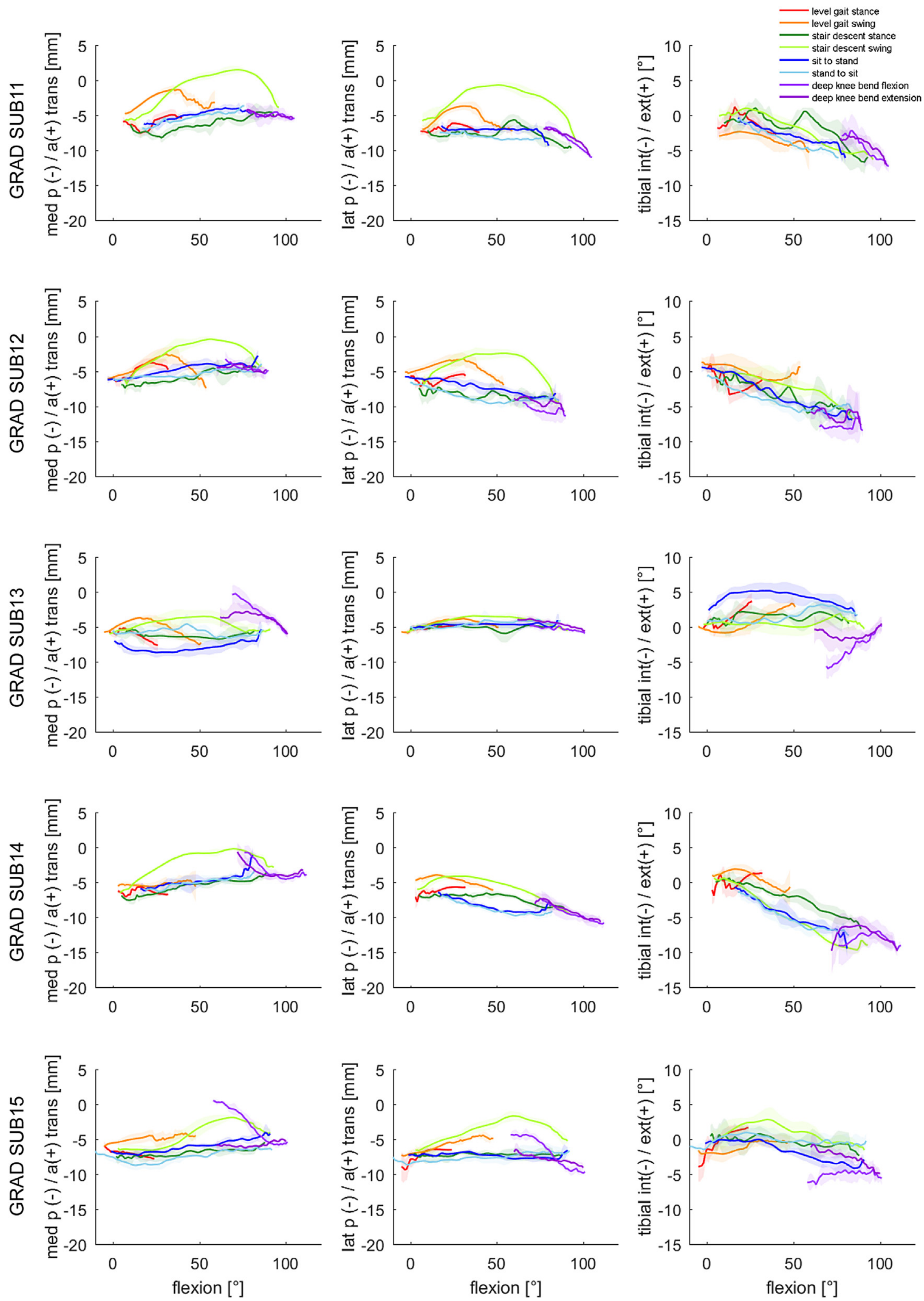

Figure A.5. AP translation-flexion-coupling and tibial rotation-flexion-coupling. Mean over all trials of GRAD subjects SUB11 to SUB15. The shaded areas represent the SD for AP translation over all trials. Data were only averaged at flexion angles for which at least data of 3 trials were available.

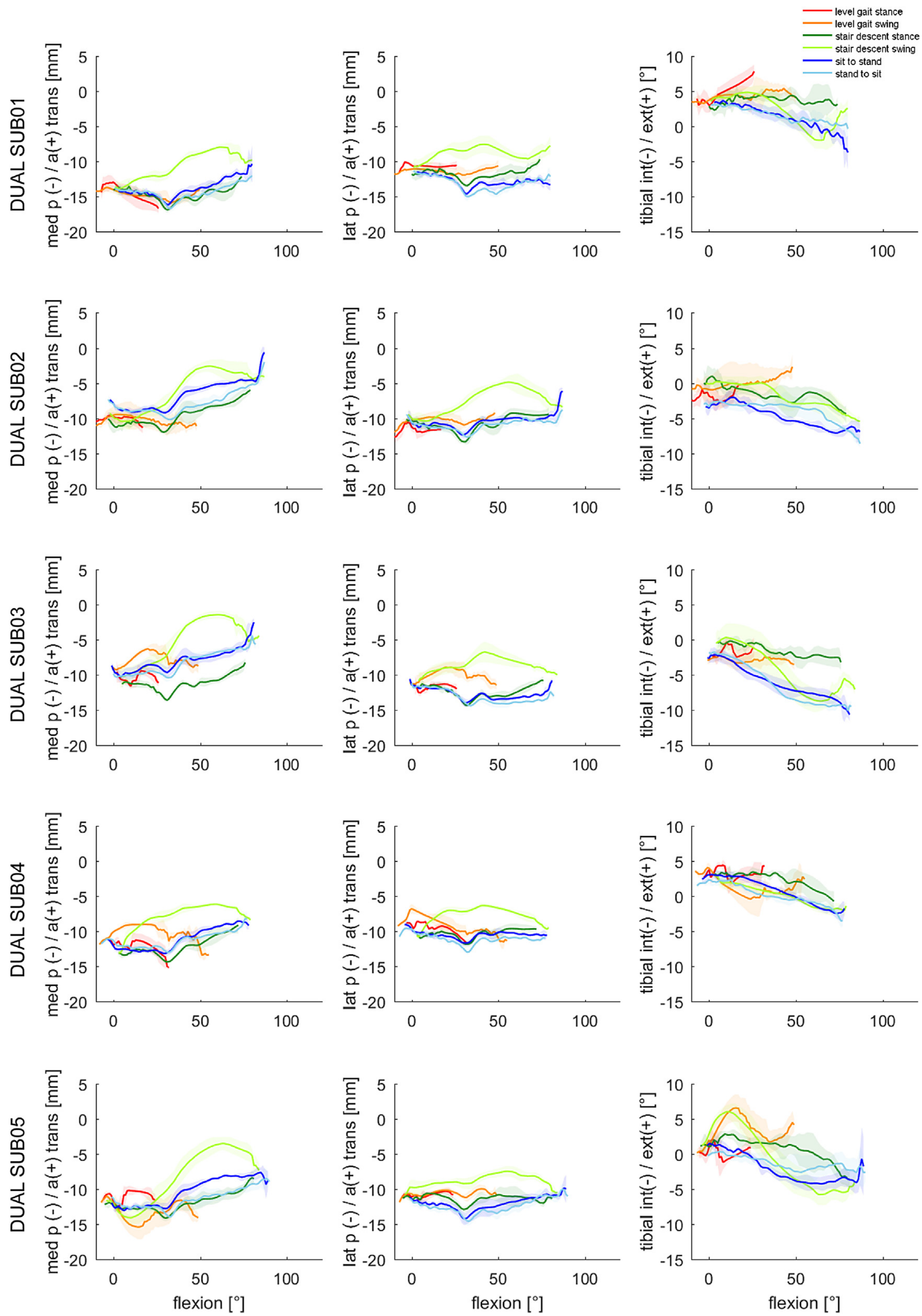

Figure A.6. AP translation-flexion-coupling and tibial rotation-flexion-coupling. Mean over all trials of DUAL subjects SUB01 to SUB05. The shaded areas represent the SD for AP translation over all trials. Data were only averaged at flexion angles for which at least data of 3 trials were available.

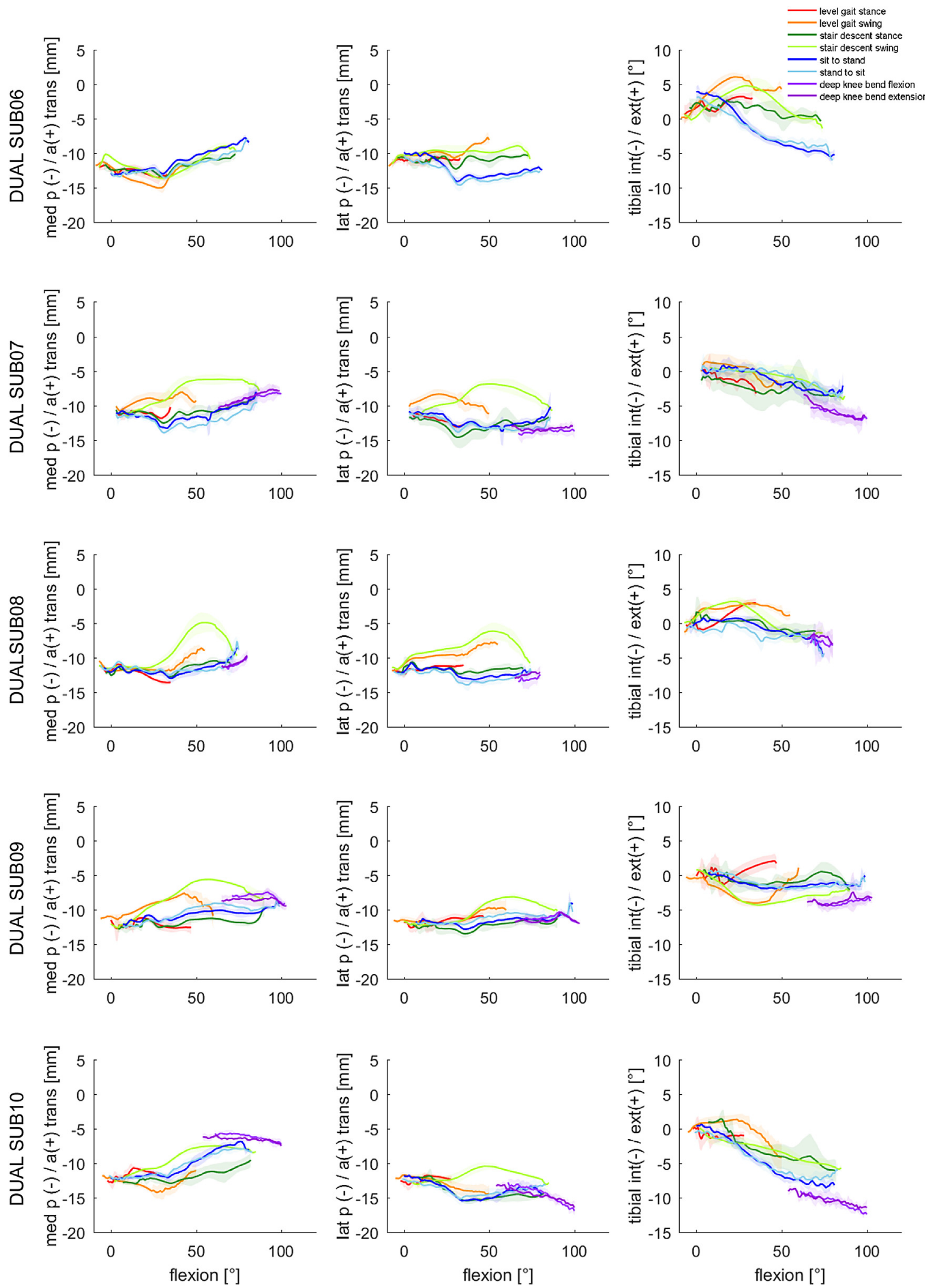

Figure A.7. AP translation-flexion-coupling and tibial rotation-flexion-coupling. Mean over all trials of DUAL subjects SUB06 to SUB10. The shaded areas represent the SD for AP translation over all trials. Data were only averaged at flexion angles for which at least data of 3 trials were available.

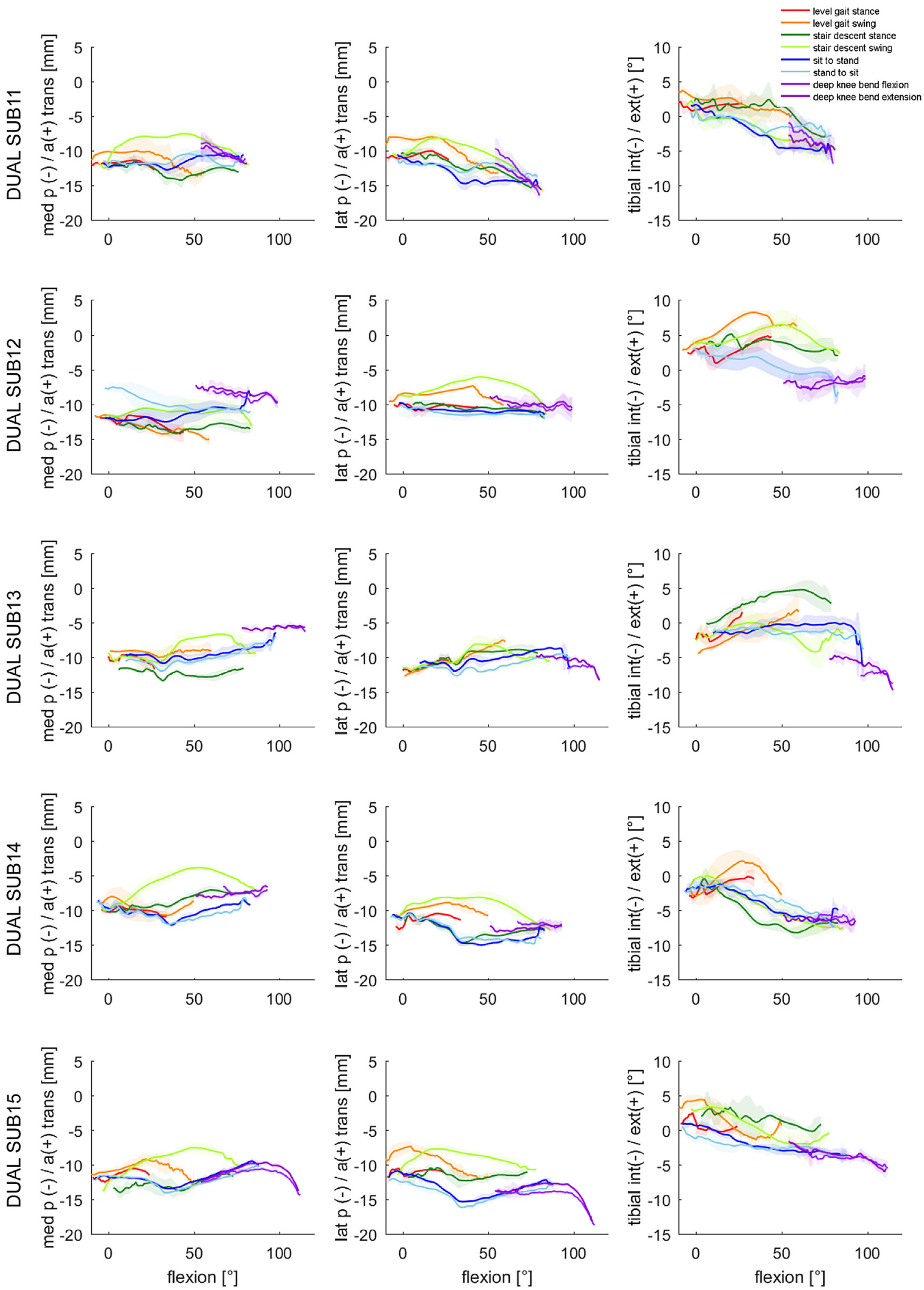

Figure A.8. AP translation-flexion-coupling and tibial rotation-flexion-coupling. Mean over all trials of DUAL subjects SUB11 to SUB15. The shaded areas represent the SD for AP translation over all trials. Data were only averaged at flexion angles for which at least data of 3 trials were available.

Appendix B

Table B.1
P Values of the Group Comparison (2-Tailed Unpaired *t*-Test) for Sagittal, Frontal, and Transversal Knee Rotations.

Task	Flexion-Extension			Adduction-Abduction			Internal-External Rotation		
	Cycle	Stance	Swing	Cycle	Stance	Swing	Cycle	Stance	Swing
Level gait	0.953	0.494	0.792	0.502	0.110	0.864	0.966	0.631	0.098
Stair descent	0.028	0.019	0.022	0.050	0.948	0.091	0.209	0.410	0.128
Sit to stand	0.788			0.376			0.180		
Stand to sit	0.693			0.890			0.857		
DKB flexion	0.610			0.040			0.127		
DKB extension	0.557			0.050			0.416		

DKB, deep knee bending.

Table B.2
P Values of the Group Comparison (2-Tailed Unpaired *t*-Test) for Medial and Lateral AP Translation.

Task	AP Translation Medial			AP Translation Lateral		
	Cycle	Stance	Swing	Cycle	Stance	Swing
Level gait	0.364	0.194	0.732	0.201	0.093	0.886
Stair descent	0.999	0.504	0.996	0.236	0.831	0.041
Sit to stand	0.773			0.016		
Stand to sit	0.042			0.007		
DKB flexion	0.152			0.928		
DKB extension	0.648			0.843		

AP, anteroposterior; DKB, deep knee bending.