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# Range of motion and repeatability of knee kinematics for 11 clinically relevant motor tasks

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ABSTRACT

Standard gait analysis reports knee joint rotations in the three anatomical planes without addressing their different levels of reliability. Most clinical studies also restrict analysis to knee flexion–extension, because knee abduction–adduction and axial rotation are small with respect to the corresponding amount of measurement artefact. This study analyses a set of 11 motor tasks, in order to identify those that are adequately repeatable and that can induce greater motion at the knee than walking. Ten volunteers (mean ± SD age: 29 ± 9 years) each underwent three motion analysis sessions on different days with a standard gait analysis system and protocol. In each session they performed normal walking, walking with sidestep and crossover turns, ascent onto and descent off a step, descent with sidestep and crossover turns, chair rise, mild and deep squats, and lunge. Range and repeatability of motions in the three anatomical planes were compared by ANOVA. The sidestep turns showed a range of axial rotation significantly larger than that in walking (about 8°), while maintaining similar levels of repeatability. Ascent, chair rise, squat, and lunge showed greater flexion ranges than walking; among these, ascent was the most repeatable. The results show that turning increases knee axial rotation in young subjects significantly. Further, squats and lunges, currently of large interest in orthopaedics and sports research, have smaller repeatability, likely accounted for to the smaller constraints than in the traditional motor tasks.



## 1. Introduction

*In vivo* measures of knee joint kinematics can facilitate the quantitative evaluation of clinical conditions, particularly in the context of knee replacement. Previous studies compared knee rotations of various clinical populations, including the same knees before and after replacement [1,2], replaced versus normal knees [1–9], replaced knees with different prosthesis designs or surgical procedures [9–11], and pathological versus non-pathological knees [12,13]. These data have been obtained with various methods, including fluoroscopy [9], goniometry and accelerometry [1–3,12–14], but mainly skin marker-based movement analysis [4–11]. The latter presents unique advantages over the others but also considerable challenges. Although motion capture systems are not yet as portable as smaller devices nor as precise as fluoroscopic analyses, they can noninvasively measure whole body motion in three dimensions, during complex functions as frequently performed in daily life.

Marker-based motion tracking studies on the knee have mainly focused on level walking [6,8–10,15,16]. A limited number have studied step-up, -down, and -over manoeuvres [4,8–10], obstacle avoidance [5], and chair rising [7,17]. Other studies used different methodological approaches to analyse ascent [9] and chair rise [2,3,9,13,14,18,19]. Frequently only knee flexion–extension was analysed in these studies because these motor tasks induce small out-of-sagittal plane knee rotations, both in healthy and replaced joints [6,15,16]. Moreover, measurement variability is introduced by marker tracking error, skin motion artefacts, and marker placement or frame definition errors [20–22]. The overall error and variability across repeated trials, therefore, is expected to exceed the small out-of-sagittal plane knee rotations involved in many motor tasks [21,23–26]. This

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hinders the detection of differences in skeletal kinematics among populations.

To overcome these limitations that accompany standard gait analysis, the ratio between skeletal joint kinematics and relevant measurement errors should be improved, either by reducing the errors or enlarging the joint range of motion. This study investigates the latter direction. Progress in error reduction includes the development of more robust hardware, tracking devices, marker sets, and analysis techniques [22,24,26], although the main source of error is associated with soft tissues [21]. An interesting additional approach is to enlarge the spectrum of analysed motor tasks. Ideal tasks would be as repeatable as walking, while inducing larger knee rotations, thereby reducing the error-to-measurement ratio. Consequently a change in range of motion (ROM) among pathologic patients would be more detectable than in walking, especially for the out-of-sagittal knee rotations.

The purpose of this study was to identify motor tasks in which knee joint rotation in the three anatomical planes is both large and repeatable. These would best suit more detailed clinical gait analysis studies on knee treatments. The potential tasks were chosen based on availability of published data for comparison, and on the hypothesis of achieving greater abduction–adduction or axial rotation than during gait. Previous similar studies that have analysed series of tasks *in vivo* used simple goniometry and reported only on knee flexion [1,2,13,14].

## 2. Materials and methods

Approval for this study was given by the ethics committee of Leuven (Pellenberg) University Hospital, Belgium. Ten adult subjects (9 male, 1 female; age: $29 \pm 9$ years; body-mass index (BMI): $25 \pm 5$) volunteered to participate after giving informed consent. None had a known history of musculoskeletal or neurological pathology, except for one male subject who was treated 1 year earlier for a right Achilles tendon rupture.

Three-dimensional (3D) motion analysis was performed using an optical data capturing system (Vicon Motion Systems, UK) with eight to fourteen cameras, which determined the 3D trajectories of 23 passive retro-reflective markers (14-mm diameter), located on the lower limbs, pelvis, and trunk (Total body Plug-in-Gait marker set [15,16,27] with Knee Alignment Device, KAD [28], Vicon, Oxford, UK). The infrared cameras collected data at 100 Hz. Kinematics were calculated based on marker trajectories by using Euler angles and specific anatomically aligned joint coordinate systems. Ground reaction force was also collected at 1000 Hz from two forceplates (AMTI, Watertown, MA, USA), but for gait cycle definition only.

Each subject underwent three motion capture sessions, each 0–56 days apart (median: 7 days), conducted by one well-trained physical therapist. During each session, the subject was asked to perform three trials of each of the following 11 motor tasks:

1. Walking: Walk on a level floor in a straight direction at a self-selected speed.
2. Walk and crossover turn (Fig. 1a): After initially walking forward, pivot over the forceplate and change direction by 90° toward the side of the pivoting leg.

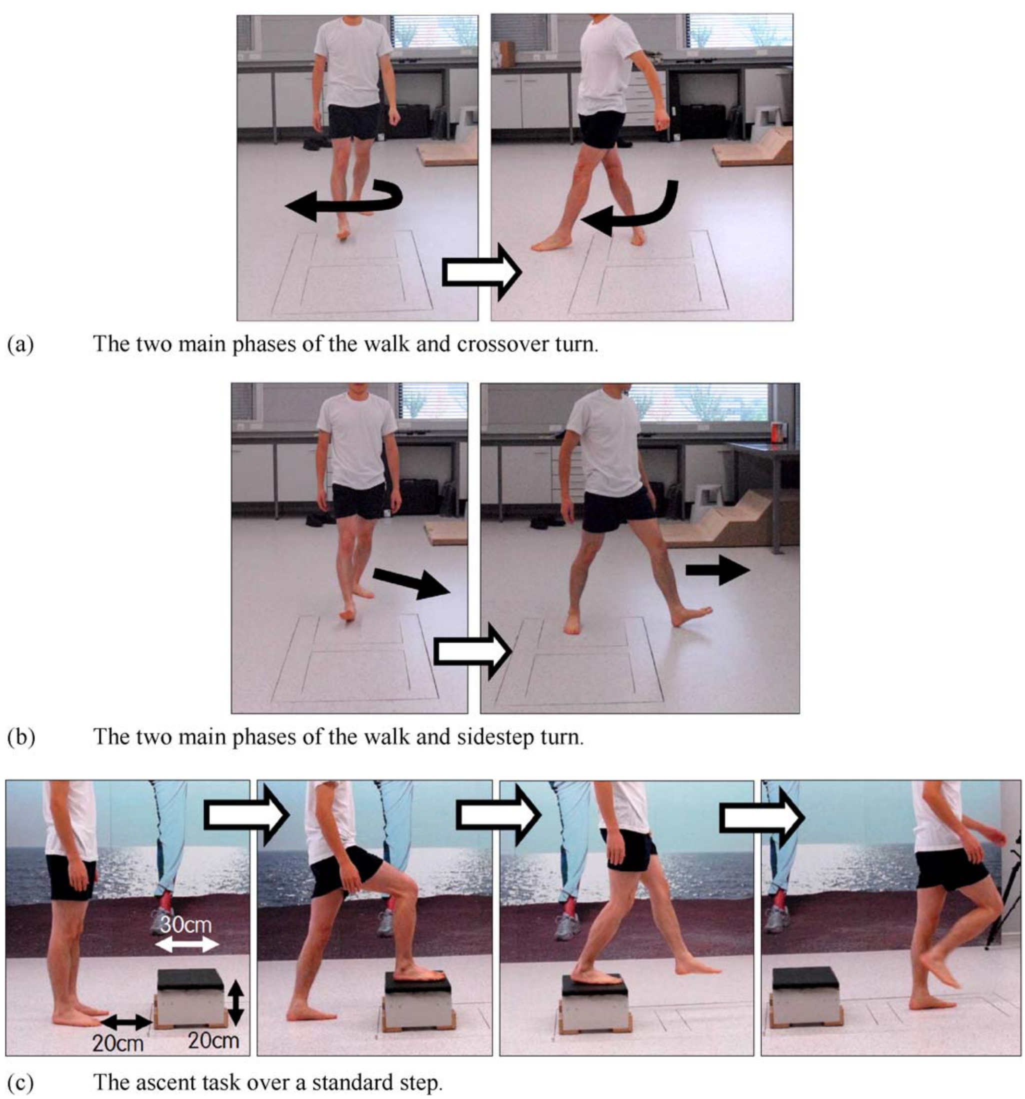


**Fig. 1.** Images of the pivoting tasks and ascent over a standard box. (a) The two main phases of the walk and crossover turn. (b) The two main phases of the walk and sidestep turn. (c) The ascent task over a standard step.

Internal rotation at the pivoting knee, i.e. internal rotation of the tibia in the femur reference frame, is expected, which would result from a combination of external rotation of the femur and a possible internal rotation for the tibia, similarly to a previously reported crossover turn [17].

3. Walk and sidestep turn (Fig. 1b): As in the previous task, walk forward, then pivot over the forceplate by 90° toward the side opposite to the pivoting leg. External rotation of the pivoting knee is expected, mainly associated to internal rotation of the femur, similarly to a previously reported sidestep turn [17].
4. Ascent onto a step (Fig. 1c): With one leg, step onto and over a 20 cm high step over the forceplate, as previously described [10], and continue straight. The step length and width were 30 cm × 45 cm. Subjects started with toes 20 cm away from the step.
5. Descent off a step: Descend from the same step as in stair ascent onto the forceplate and walk forward.
6. Descent with crossover turn: Descend from the step onto the forceplate, and perform a crossover turn by pivoting on the descending leg.
7. Descent with sidestep turn: Descend from the step onto the forceplate, and perform a sidestep turn by pivoting on the descending leg.
8. Chair rise: Rise up from a 90° knee flexion sitting position into a full standing position, with feet over separate forceplates and the hands and arms free. An adjustable height stool was used for the seat.
9. Squat, mild: Squat down to less then 90° knee flexion with feet over separate forceplates, with minimal exertion, and rise back up. Heels could lift from the floor.
10. Squat, deep: Squat down as far and safely as possible, with feet over separate forceplates, and rise back up. Heels could lift from the floor.
11. Lunge: Bend one knee in front of the body to approximately 90° flexion, planting that foot on a forceplate, and then rise back up.

The left leg was analysed for each task except for the crossover turns, for which the right leg was analysed, which kept the turn direction constant. Trials were averaged for each subject, resulting in sample sizes of 10 subjects for each task except the deep squat. Two high-BMI subjects (BMI 32 and 35) attempted but ultimately declined to perform the deep squat, resulting in 8 subjects for this task.

Movement cycles were defined according to foot contact with forceplates and by analysing foot marker trajectories. Both stance and swing phases were analysed in all the walking and ascent/descent tasks. The start of chair rise was the time at which the upper body began to lean forward, and the end was the time of maximal knee extension. Squat cycles were defined according to when the knee flexed away from and returned to full extension. The lunge cycle started at initial footstrike in front of the body and ended at final footstrike near standing position. All data were normalized to a 0–100% time cycle.

The data were reduced by measuring the extremes and relevant ROMs of the kinematics curves for each subject, and by averaging these measurements within and between subjects for each task. Measures of absolute intra- and inter-subject variability of the three knee rotations for each task were calculated by finding the root-mean-square of the error (RMS) of each trial against the average trial, across the whole movement cycle (Fig. 2). Lower variability implies increased repeatability. The extreme, ROM, and RMS values for the tasks were compared within each of the three knee rotations using statistical software (Minitab, State College, PA, USA). Multiple outcome one-way ANOVA was performed for the comparison, after confirming normality of the distributions and noting the nearly equal sample sizes. Bonferroni's test against a control was used to find paired differences from walking. All significance thresholds were $\alpha = 0.05$. Adjusted *p*-values are reported to account for the multiple outcomes testing.

## 3. Results

The tasks showed considerable differences in repeatability of knee kinematics, as evidenced by the inter- and intra-subject RMS values (Fig. 3). For sagittal plane motion, all the tasks were less repeatable than walking and had larger inter-subject RMS values. These were between 5.8° in walking and crossing over, and 18.3° in deep squat, which compare with the 4.6° in walking. Ascent, chair rise, squat, and lunge also showed significantly larger mean intra-subject RMS values for the sagittal plane motion (between 5.5° and 11° vs. 2.7° in walking, $p < 0.006$). For the out-of-sagittal plane knee rotations, walking and descent tasks showed the highest repeatability.

Average maximum and minimum values of the three knee rotations revealed remarkably different ROMs among the motor tasks, which was consistent across the subjects analysed (Table 1, Fig. 4). Regarding sagittal knee motion, the tasks of ascent onto a step, chair rise, deep squat, and lunge all had significantly greater ROM than typical walking ($p < 0.002$), with the maximum found for deep squat (95.4°). Regarding knee abduction–adduction, the squats showed significantly smaller ROM than walking (4.8° or 4.9° vs. 8.3°, $p < 0.047$). Regarding axial rotation, the ROMs for sidesteps while walking (22.2°) or descending (23.9°) were significantly greater than for normal walking (14.4°, $p < 0.004$).

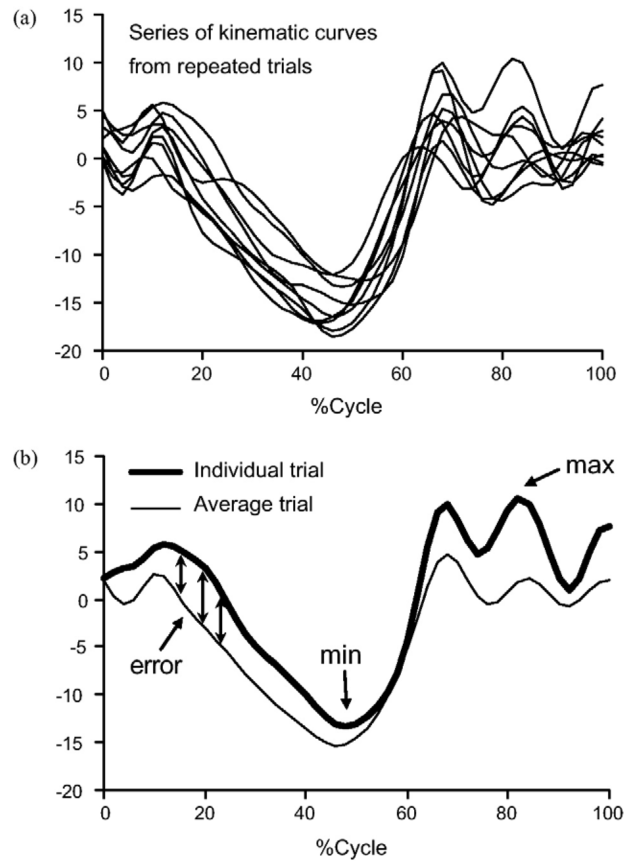


**Fig. 2.** Example of the measurements taken on all kinematics curves. (a) Set of original tibial in/external rotation curves during walking with sidestep turn. (b) The maximum, minimum, and range of motion (max–min) of each individual curve was found. Variability of the group of curves was calculated by taking the root-mean-square of the error, or distance, from the average curve at each %cycle, which estimates the deviation of all the individual trials from the average trial.

The extremes of the kinematics curves also exhibited significant differences among the tasks. Peak knee flexion angles for ascent, chair rise, mild squat, deep squat, and lunge ranged from 78.6° to 106.1°, and all were significantly greater than for walking (63.7°, $p < 0.012$). Maximum knee internal rotation for the crossover turns, ascent, chair rise, and squats ranged from 15.8° to 22.4°, and all were greater than for walking (10.2°, $p < 0.048$). Minimum knee internal rotation for ascent and squats ranged from 0.3° to 2.6° and were greater than for walking (−4.2°, $p < 0.028$), while the minimum angles for the sidestep turns ranged from −10.5° to −11.0° and were lower than for walking, or more externally rotated ($p < 0.001$).

## 4. Discussion

Motion of the human knee joint in the three anatomical planes was measured in 11 different motor tasks using a standard gait analysis technique. The results demonstrated that in more demanding motor tasks of daily living, such as sidestep turn and step descending, the knee experiences joint rotations that are significantly larger than during standard walking, but still very repeatable. This holds even when giving subjects minimal instructions. A sidestep turn while walking or descending induces

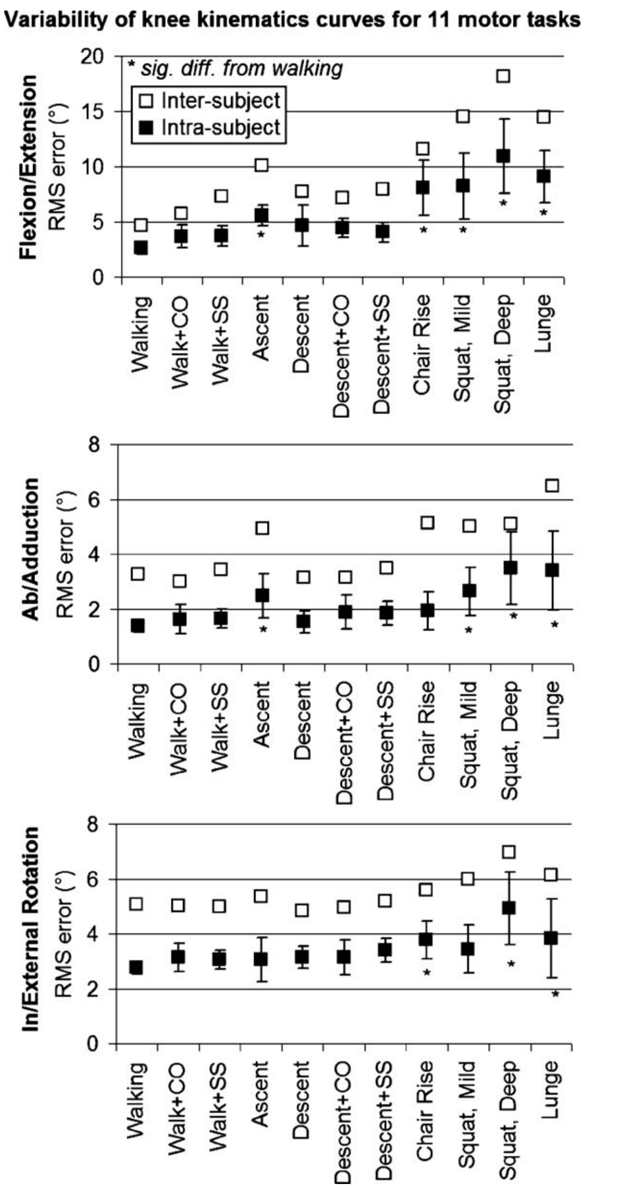


**Fig. 3.** Inter-subject and average intra-subject RMS errors of the kinematics curves for the three knee rotations, across all subjects, for each motor task. RMS values are similar to standard deviation of the errors. Asterisked tasks showed statistically significant paired differences in the RMS values compared to walking. "CO" and "SS" indicate crossover and sidestep turns, respectively.

a greater axial ROM than typical walking by 8–9°, while maintaining similar levels of repeatability. Ascent onto a step induces larger flexion ROM than walking by approximately 20°, concurring with previous studies which additionally showed the sensitivity of knee flexion to clinical condition [1,2,9,13,14]. Chair rise, deep squat, and lunge also showed larger flexion ranges but had worse repeatability.

To better understand these results, it is crucial to place them in the context of measurement error, which affects both repeatability and accuracy. Clinical gait analysis fully relies on the repeatability of measurements, since conclusions are based on multiple follow-ups of a single subject, or on studies of multiple subjects in different populations. Consequently, repeatability of the techniques has been the focus of previous studies on walking [16,23]. Notably, the repeatability of knee internal–external rotation during turning tasks was found to be similar to the straight-ahead tasks, even between subjects and sessions. This higher level

**Table 1**
Average extremes and ranges of motion (ROM) of knee kinematics curves, for 11 motor tasks from 10 different subjects, in degrees (°). "CO" and "SS" indicate crossover and sidestep turns, respectively.

| Task | Max | Min | ROM |
|---|---|---|---|
| Knee flexion+/extension− | | | |
| Walking | 63.7 ± 5.2 | 2.6 ± 3.7 | 61.1 ± 5.0 |
| Walk + CO | 63.9 ± 3.5 | 6.2 ± 2.6 | 57.7 ± 4.2 |
| Walk + SS | 58.7 ± 6.0 | 1.1 ± 4.8 | 57.5 ± 8.0 |
| Ascent | 94.6* ± 6.1 | 11.0 ± 3.1 | 83.6* ± 5.3 |
| Descent | 65.7 ± 6.4 | 4.8 ± 2.7 | 60.9 ± 6.2 |
| Descent + CO | 63.4 ± 3.0 | 7.3 ± 2.0 | 56.1 ± 3.7 |
| Descent + SS | 57.7 ± 7.4 | 3.1 ± 3.4 | 54.6 ± 8.0 |
| Chair rise | 85.7* ± 5.4 | 4.4 ± 4.6 | 81.3* ± 6.6 |
| Squat, mild | 78.6* ± 16.0 | 8.5 ± 5.7 | 70.1 ± 18.3 |
| Squat, deep | 106.1* ± 22.2 | 10.7 ± 5.1 | 95.4* ± 25.4 |
| Lunge | 97.3* ± 13.9 | 16.6 ± 7.1 | 80.7* ± 11.7 |
| Knee adduction+/abduction− | | | |
| Walking | 8.2 ± 2.9 | −0.1 ± 3.0 | 8.3 ± 2.5 |
| Walk + CO | 5.0 ± 2.7 | −2.1 ± 2.3 | 7.1 ± 2.4 |
| Walk + SS | 7.6 ± 2.7 | 0.4 ± 3.5 | 7.1 ± 3.3 |
| Ascent | 10.0 ± 3.7 | −0.7 ± 3.1 | 10.7 ± 1.9 |
| Descent | 7.7 ± 2.5 | −0.2 ± 2.2 | 8.0 ± 2.2 |
| Descent + CO | 5.7 ± 2.3 | −2.2 ± 2.3 | 8.0 ± 2.1 |
| Descent + SS | 7.9 ± 3.4 | 0.3 ± 3.0 | 7.6 ± 2.8 |
| Chair rise | 7.0 ± 2.3 | −0.9 ± 2.1 | 7.9 ± 1.8 |
| Squat, mild | 4.3 ± 3.5 | −0.5 ± 4.7 | 4.9* ± 2.8 |
| Squat, deep | 5.0 ± 2.7 | 0.2 ± 3.7 | 4.8* ± 2.4 |
| Lunge | 8.3 ± 3.8 | −0.7 ± 5.1 | 9.0 ± 3.4 |
| Knee tibial internal+/external− rotation | | | |
| Walking | 10.2 ± 3.4 | −4.2 ± 2.6 | 14.4 ± 4.1 |
| Walk + CO | 16.3* ± 4.0 | −3.0 ± 3.2 | 19.3 ± 5.2 |
| Walk + SS | 11.7 ± 4.3 | −10.5* ± 3.2 | 22.2* ± 4.0 |
| Ascent | 15.9* ± 4.2 | 0.3* ± 3.6 | 15.6 ± 4.6 |
| Descent | 11.6 ± 3.3 | −2.4 ± 1.3 | 14.0 ± 2.9 |
| Descent + CO | 15.8* ± 3.8 | −2.4 ± 3.5 | 18.3 ± 3.8 |
| Descent + SS | 13.0 ± 3.0 | −11.0* ± 3.8 | 23.9* ± 4.8 |
| Chair rise | 17.7* ± 5.4 | −0.1 ± 3.9 | 17.8 ± 5.0 |
| Squat, mild | 17.9* ± 4.2 | 1.8* ± 3.1 | 16.0 ± 4.3 |
| Squat, deep | 22.4* ± 6.5 | 2.6* ± 1.6 | 19.7 ± 6.7 |
| Lunge | 15.3 ± 5.2 | −2.5 ± 4.6 | 17.7 ± 5.5 |

$n = 10$ for each task, except for deep squat where $n = 8$.
* Significant difference with respect to the value for walking.

of repeatability, combined with a larger ROM, suggest that the turning tasks may be preferable for a number of clinical investigations.

Accuracy must also be considered in addition to repeatability. In human kinematic analyses, accuracy refers to the difference between the observed measurements obtained with external, i.e. skin mounted, references and the real internal skeletal motion. Invasive bone tracking [22] was not performed here, but the extent of measurement inaccuracy likely associated with skin markers can still be inferred, based on the knee abduction–adduction curves. A small ROM for abduction–adduction is expected in normal knees, and large deviations in abduction–adduction suggest measurement inaccuracy [21,23,29]. Previous investigations also showed that larger flexion range, as observed in a number of the present motor tasks, can be associated with larger measurement inaccuracy [21]. Despite this, the ranges of abduction–adduction interestingly were found to be comparable to or even smaller than in walking, except possibly for ascent and lunge. These smaller abduction–adduction ROMs may suggest that the KAD procedure helped reduce crosstalk errors sufficiently.

Previous literature provides also quantitative insight into the amounts of this error which could have affected the present results. During walking and other motor tasks, measurement inaccuracy associated with skin markers can exceed considerably the true skeletal motion [21,29,30,33–35]. In particular, because of the distribution of the soft tissues about the long bones of the lower limb, joint axial rotation is much affected [21,29]. Within the motor tasks analysed, it is expected that the skin motion artefact

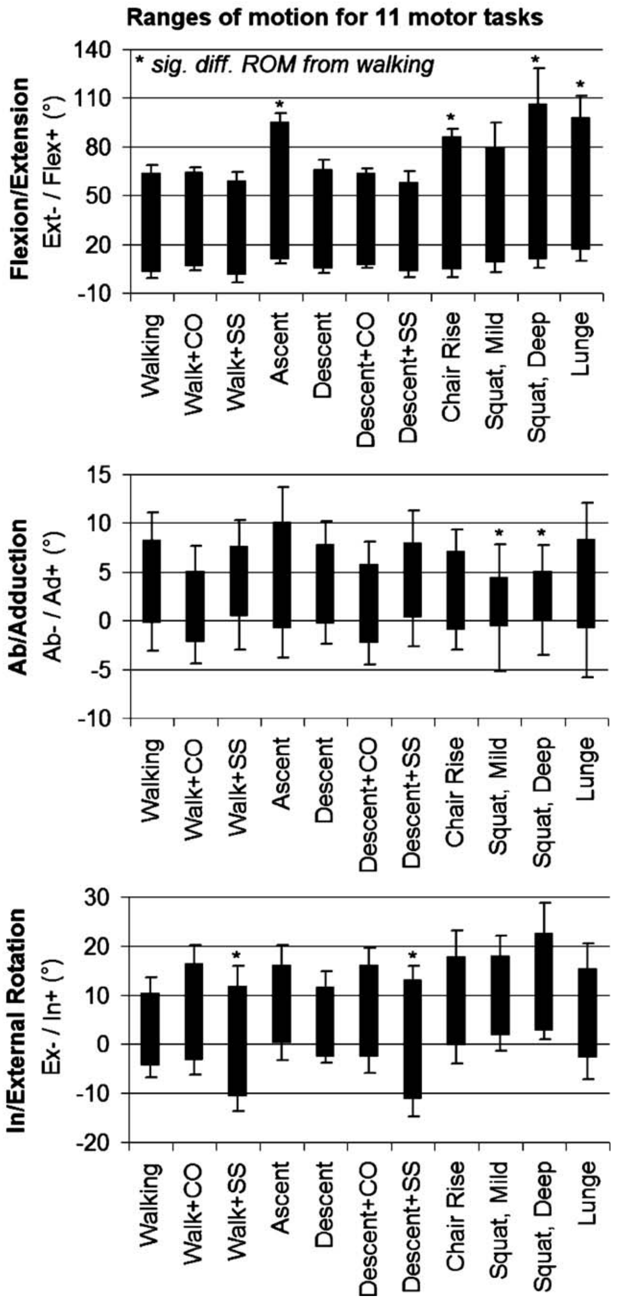


**Fig. 4.** Bar charts mapping the mean ROM (between the maximum and minimum value) of the three knee rotations, across all subjects, for each motor task. Whiskers represent 1SD of the maximum or minimum values. An asterisk notes a task with a statistically significant pairwise difference for the ROM compared to walking. "CO" and "SS" indicate crossover and sidestep turns, respectively.

can be larger in descending tasks as for the higher impacts, in the large-knee-flexion tasks as for the larger skin sliding around the joint, and in the turning tasks as for the larger skeletal internal–external rotation at the joints. In the latter however, the error in percentage of the physiological motion can be smaller because in fact of the larger axial ROM. For example, axial ROM in the range 18–24° was observed in the present study for 90° turning tasks, which may be compared with a corresponding mean maximum error of 5.4° associated with skin motion [30], though obtained in jump-cutting maneuver. Finally, it must be pointed out that the inter-subject variability of the soft-tissue artefact is very large [21] and therefore relevant consistent patterns over a large population of even normal subjects are unlike.

The most repeatable tasks were walking and descent, with and without turns. Only the sidestep turns showed significantly larger axial rotation ROM than walking, though the crossover turns showed the same trend. This is possibly due to a combination of smaller range of motion and higher variability for the crossover turns. Previous studies on similar crossover tasks suggest that a larger sample size would have revealed a statistical difference [17,31]. Another previous study demonstrated recovery of knee flexion ROM in total knee replacement by analysing a set of motor tasks over multiple follow-ups [2]. Based on the present results, knee axial rotation can also be included in similar future studies. In particular, these tasks can aid the functional assessment of axial rotation in mobile-bearing versus fixed-bearing knee implants, or of single- versus double-bundle anterior cruciate reconstructions.

Standardisation and instruction are expected to improve the repeatability of the tasks. For example, during crossover turns, subjects were observed to inconsistently point the toes of the pivoting leg in the direction of the turn before heel strike. This made any increases in axial ROM more difficult to distinguish statistically from walking. Standard instructions or training might have prevented this. Additionally, the effect of arm positions on ground reaction forces during chair rise already has been studied [19], but similarly rigorous work should be done for knee kinematics. Knee flexion ROM during chair rise also is affected by pathology and arthroplasty [2,7], and more robust, standardised protocols may show if the out-of-sagittal rotations are similarly affected. The squat is of particular interest for *in vitro* knee simulator studies [32], but *in vivo* it can be performed in a variety of ways. Further work is warranted to study the effects of limb and trunk positions, movement speed, and other factors on these motor tasks. Care also must be taken when employing any standardisation method, since each attempt to control a motor task raises possible questions about the clinical relevance of the task.

The strengths and limits of the present study are those of most current clinical gait analyses. Additional measurements, such as spatio-temporal parameters, kinetics, or muscle activation, can be reported with the present technique, which can be the focus for future studies. For example, temporal data allows the analysis of joint angular velocities or task completion times [3,7]. Also the out-of-sagittal plane rotation data could be plotted versus knee flexion, which would facilitate comparison with many cadaver studies [32]. Other limitations specific to this study can be addressed in the future. Additional populations are of interest besides young subjects. Studies of pathologic, asymmetric patients also must more rigorously consider the issue of which leg to study. Finally the present results could be confirmed with more accurate tools like fluoroscopy or bone-pin studies, in order to reveal these kinematic differences at the skeletal system. However, until such tools can analyse the whole body non-invasively, skin-marker-based gait analysis will remain the only comprehensive and practical clinical tool available.

These results imply two central conclusions. First, turning increases knee axial rotation in young subjects significantly. The amount of axial rotation and the between trial variability vary from subject to subject, but among the population analysed a general pattern persists and this can be investigated further. Second, squats and lunges tasks, which are currently of great interest in orthopaedic and sports research, have smaller repeatability likely because subjects are allowed to perform these with less instructions and constraints.

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## Conflict of interest statement

All authors have contributed to and reviewed the material in this report. None of the authors have a conflict of interest in reporting this study.

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