INTRODUCTION
Numerous studies have demonstrated the beneficial role of gait analysis in the planning and evaluation of surgical treatments at the human knee joint, but most confine their research to flexion-extension during individual tasks, such as normal walking [1,2]. Nevertheless, the current variety of knee surgical treatments encourages kinematic studies on more demanding locomotor activities, such as crossover cutting, ascending or descending a stairway, or turning, to obtain a thorough picture of healthy and atypical patterns. Furthermore, very little is known about the three-dimensional (3D) kinematics of the knee during these more complex motor tasks [3]. Also, repeatability data on 3D knee rotations during these tasks are not widely available, preventing easy involvement of certain tasks in motion analysis studies, since the quality of measurements from many of these tasks is unknown. Nevertheless, all these data are necessary for more careful designs of future clinical experiments.

Therefore, the present study describes the kinematics of the three knee joint rotations in healthy subjects for eleven daily life motor tasks [3]. Also, repeatability data on 3D knee rotations during these tasks are not widely available, preventing easy involvement of certain tasks in motion analysis studies, since the quality of measurements from many of these tasks is unknown. Nevertheless, all these data are necessary for more careful designs of future clinical experiments.

METHODS
Upon ethical approval, ten adult subjects participated in this study after giving informed consent. They included nine males and one female, with mean age 29 (SD 9) years, range 22-47 years; weight mean 76 (SD 20) kg; height mean 178 (SD 8) cm, body mass index mean 24 (SD 5). No subjects reported any condition that could affect their functional performance.

Kinematic data were obtained using a fourteen camera motion capture system tracking the 3D positions of 23 retro-reflective spherical markers fixed according to the Plug-in-Gait marker protocol (Vicon, Oxford, UK). A knee alignment device was used to identify the knee flexion/extension axis. During each session, the subject was asked to perform eleven different motor tasks with three repetitions each, gait tasks: walking, walk and crossover turn (WCO), walk and sidestep turn (WSS), ascent onto a step (SA), descent off a step (SD), descent with crossover turn (SDCO), descent with sidestep turn (SDSS); Non-gait tasks: chair rise (CR), mild squat (MS), deep squat (DS), lunge (L). This specific set of motor tasks was selected because some of these induce greater motion at the knee joint [4]. To remove inter-observer repeatability, the same well-trained physiotherapist performed all the gait tests. All data were normalized to a 0-100% time cycle. For chair rise and squat, the cycles were defined by visually analyzing the main body segments. The start of chair rise was defined as when the upper body began to lean forward, and the end was at the time of maximal knee extension. Squat cycles were defined between times of maximal knee extension. The lunge cycle was defined between foot-strike and lift-off. Corresponding kinematics curves were grouped together according to subjects and tasks and averaged at each percentage cycle. Various spatio-temporal parameters were extracted from each of the resulting knee rotation curves.

Repeatability was assessed within subjects as well as between subjects, the latter quantifying the variability within a group of normal subjects. Repeatability of the joint rotations, both within and between subjects, was quantified in relative terms by the coefficient of multiple correlation (CMC) [5] and, in absolute terms, by the root-mean-squared difference (RMS) against the average. Inter-subject variability of the kinematic and temporal parameters extracted from the curves was characterized by the standard deviation (SD), coefficient of variation (CV) [5], and the two-way mixed model intraclass correlation coefficient (ICC). Measurements were considered to have “good” repeatability if they showed a high ICC (0.8 to 1), low SD (<5°), low CV (<15%), or any combination of the three [2].

RESULTS AND DISCUSSION
The tasks showing the largest internal rotation were the crossover turns (17°) and the high-flexion tasks of SA, CR, MS, DS and L (17° to 25°). The tasks showing the largest external rotation were the WSS, SDSS (11.1° and 12.0°). WCO and SDCO also showed smaller adduction peaks (5.7° and 6.4°), compared to normal walking (8.7°). Among the gait tasks, stride times ranged from 1,049 s for W to 1,507 s for SA. 3D knee kinematics for the non-gait motor tasks (CR, MS, DS, and L) have not been previously reported
within the same subject sample, as in this study. Results for these tasks show consistent coupling between flexion-extension and axial rotation curves (Figure 1). Other studies similarly confirm that internal rotation occurs at the human knee joint progressively over flexion, e.g. [3].

Non-gait tasks showed worse intra-subject repeatability compared to gait tasks, particularly in abduction-adduction, as demonstrated by CMC and RMS values (Table 1). Furthermore, the average knee abduction-adduction curves for chair rise (Figure 1), squat, and lunge were relatively smooth and of small magnitude compared to the gait tasks. This was unexpected, since the larger flexion ranges of these tasks were hypothesized to lead to more crosstalk errors and larger abduction-adduction ranges. The smaller ranges instead may be attributed to the typical stabilization of the knee during the permanent weight-bearing conditions in the chair rise, squat, and lunge. A number of parameters with good intra-subject repeatability were found for gait and non-gait tasks. Regarding relative repeatability, the most repeatable among the gait tasks were mid-swing maximum flexion and its corresponding %cycle, and stride time. For each of these parameters, the CV was under 15%, with most tasks showing CV under 10% and ICCs above 0.90. Regarding absolute repeatability, the most repeatable were maximum adduction and internal rotation, with SD values mostly smaller than 5°, which was recommended as the highest threshold for the SD of clinical joint kinematics measurements [2]. This variability analysis on derived parameters has helpful implications for future clinical studies. The parameters presented here for younger, healthy subjects may be analyzed for other populations and compared. The SD and ICC values can be used to estimate the "smallest real difference" [7]. This number can also be used in a power analysis to predict the sample sizes necessary for relevant clinical studies.

CONCLUSIONS
The many different motor tasks analyzed here revealed a large spectrum of inter-subject repeatability and inter-subject variability, and also very different patterns and ranges of knee joint motion, in flexion-extension but also in out-of-sagittal plane rotations. The least constrained motor tasks, such as lunge and squat, were also the least repeatable. Finally, larger joint rotations were more repeatable. Although future studies with improved motion analysis protocols may further increase repeatability indices, all this knowledge is a good reference for the design of future gait analysis studies in pathological conditions, in particular for selecting the most suitable tasks to be analyzed when validating, for example, the claims of prosthesis designers or surgical and clinical hypotheses.

REFERENCES