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TECHNICAL NOTE

A chair with a platform setup to measure the forces under each thigh when sitting, rising from a chair and sitting down

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Abstract This paper describes the design, technical characteristics and first results of an adjustable instrumented chair with a sitting surface that records the forces under each thigh. The seat includes a force platform assembly suitable for measuring the magnitude, position and direction of the force applied to each thigh while sitting or rising from the chair. The natural frequency of the chair fixed to the floor was found to be 14.0 ± 2 Hz with an estimated damping of $\xi = 0.20$. Static tests showed that the maximal errors were 2% of the full-scale output (726 N vertically, 164 N horizontally) for both vertical and horizontal forces. The root mean square error of the center of pressure location was estimated as 5 mm. Preliminary data on the net joint moment at the hips of one healthy subject computed with and without consideration for the forces under the thighs revealed significant amplitude differences. In conclusion, the results indicate that the characteristics of the instrumented chair are acceptable and the chair can be used to assess the biomechanics of sitting and sit-to-stand and stand-to-sit tasks in various subject populations.

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1 Introduction

By identifying the mechanical challenges of many functional tasks, biomechanical analysis of locomotor tasks has greatly contributed to rehabilitation training. Rising and sitting down are repeated many times daily [6] and can become a considerable challenge for specific patient groups with impairments at the trunk and in the lower limbs. Unlike gait, we are only just learning about the mechanics of rising from a chair, an action which is often the prerequisite to many daily and domestic activities.

Biomechanical studies of rising from a chair have provided a good description of the kinematics of this task in terms of angular and linear displacements and their derivatives (velocities and accelerations) [9, 11, 12, 15]. Earlier studies [8, 10, 15, 18] have also reported the kinetics of the sit-to-stand (SitTS) task but within a more limited scope, mainly because they were unable to measure the force and moment components under each thigh when the seated subject initiated the rising task. Therefore, the net joint moment at the hips has usually been reported only after the subject has left the chair. When we want to evaluate the biomechanics of the entire task, estimation of the hip joint moment with the 'inverse dynamics' approach calls for measurements of the force components under the thigh, the forces applied at the foot and the kinematic data. Moreover, apart from our group [16, 17], no author has yet provided the hip moments and force components under each thigh during the initial and final phases of the rising and sitting tasks, respectively. Knowing these values, it might be possible to identify useful variables predicting the unknown forces and hip moments on each side.

In patients with asymmetrical impairments, it will be important to measure the side differences in weight-bearing and in the hip moments during the entire SitTS and stand-to-sit (StandTS) tasks to better understand their motor strategies in comparison to healthy subjects. Such measurements coupled with manipulations like changing the foot position or the speed of execution might also provide physical therapists with useful information that will help them reduce their patients' asymmetry.

This paper describes the design, the technical characteristics and the procedure used to calibrate the force platforms of a new adjustable instrumented chair. It also presents preliminary results for one healthy subject with regard to the errors in the hip moments associated with neglecting the forces under the thighs in the inverse dynamics approach and the search for associations that might be useful to determine these moments before seat-off or after seat-on.

2 Materials and methods

2.1 Design

2.1.1 *Mechanical design of the chair*

The instrumented chair offers a sitting surface composed of two $25.5 \times 51.0 \times 0.95$ cm aluminum plates (10.5 kg each), one for each thigh (Fig. 1). Each plate is reinforced by an "L" beam that is bolted to the plate with a 60 neoprene sheet squeezed between the two. Each of these plates is bolted to two transducers (MC3A-3-250; see details below) and is supported by a specially built steel structure. This last component is bolted through a neoprene sheet to two superposed scissor jacks of 13 kN. The lower scissor jack is fixed to a beam that rests on the floor. The overall structure of the instrumented chair is bolted into a level aluminum plate located under the wood lab floor to increase the natural frequency and dissipate some of the vibrations.

The structure below the seating aluminum plates is composed of two steel corner beams, each welded at one end to a steel plate. These steel plates are bolted to a "U" beam through a compressed neoprene 60 durometer sheet [1]. The "U" beam is free to glide on two vertical 70 cm "L" beams, which are bolted to the steel structure attached to the upper scissor jack. The sitting-surface height, varying from 39 to 77 cm, can easily be changed by adjusting the scissor jacks. A locking system (screw compressing two flat metal surfaces on the vertical "L" beams) is integrated to secure and reinforce the selected seat level position.

2.1.2 *Sitting surface and transducers*

The sitting surface comprises four AMTI (Advanced Mechanical Technology, Inc., Newton, MA) strain gauge transducers (MC3A-3-250), two for each thigh. Each of these transducers has a capacity of 1.1 kN vertically, 560 N horizontally, 14 Nm vertically and 28 Nm horizontally for measuring the orthogonal force and moment components, respectively. The transducer cross-talk was removed using the calibration matrices provided by the manufacturer.

2.1.3 *Measurement system*

To determine the rigid body definition of the chair, the Optotrak system (Optotrak 3020; four units, Northern Digital Inc.) sampling at 60 Hz was used to record the coordinates of eight points on each transducer using a six-marker probe with a stainless steel tip. A program comprising four rigid-body transformation algorithms [5] and, at each frame, selecting the result of the algorithm giving the smallest RMS error was then used to obtain the pose (position and orientation) of each transducer. These points and ten infrared emitting diode (IRED) markers fixed on

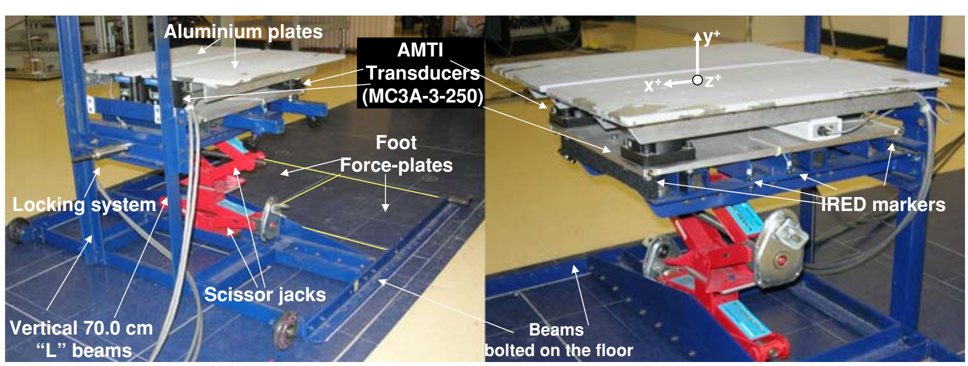

Fig. 1 Views of the chair with some components identified. The laboratory coordinate system is shown. Vertical (*Y*), antero-posterior (*X*) and medio-lateral (*Z*) positive forces are respectively upwards, towards the knee and towards the right side when a person is seated on the chair

the chair were then used with the same rigid-body program to obtain the pose of all transducers and the chair with an estimated precision of ±2 mm, ±2° horizontally and ±1 mm ±1° vertically at each frame of any trial. Using the pose of each transducer, four 3D vectors (12 force components and 12 moment components) were then transformed into a common reference system. The amplitude and direction of the resultant force and torque under each thigh were obtained from the combination of the above vectors. The maximum uniform static load was 2.2 kN vertically and 1.2 kN horizontally (combined transducer capacities).

The instrumented chair was used in conjunction with two AMTI (OR6-7-1000) force plates that measured the force and moment components under each foot. These two force-plates were bolted to the aluminum plate located under the wood floor mentioned previously. Thus, all the force measurement devices were rigidly connected to each other and to the concrete floor.

2.2 Calibration

2.2.1 *Static calibration*

The static properties of the chair were verified by applying known static forces. For the output corresponding to vertical, dead weights up to 726 N were applied on each sitting surface (total of 1,452 N). Seven 1-s measurements (0, 103, 191, 235, 490, 593, 726) were taken, after reaching steady state, during the loading and unloading process. This procedure was repeated three times.

2.2.2 *Quasi-static calibration*

The static horizontal properties of the chair were also verified by applying slow varying measured forces up to 164 N. The force was increased gradually within a full cycle of loading and unloading of about 4 s. The force measurements, of 10 s duration, were taken with a triaxial force/torque transducer (AMTI MC3A, Watertown, MA) fixed to a handle [7]. The pose of the transducer was obtained continuously from the 3D coordinates of six infrared markers rigidly mounted on its surface.

2.2.3 *Center of pressure*

The calculation of the centers of pressure (COP) [13, 14] was verified using a dead weight mounted on a customary device and applying a force (130 N) through a rolling ball bearing over both sitting surfaces. The optoelectronic system was used to record the trajectories of the 13 IRED markers installed on a rigid cylinder (30 cm × 30 cm) supported by the ball bearing. The rigid-body transformation algorithms [5] were used to compute the location of the center of the rolling ball (±2 mm) during these tests and the results were compared with those of the COP calculated by the program using the instrumented chair. The COP was calculated while the ball rolled slowly over the surface and data were acquired during eight trials of 20 s to cover the entire sitting surface of the chair.

2.2.4 *Dynamic calibration*

The dynamic response of each sitting surface (left and right aluminum reinforced plates) is affected by its natural frequency characteristics. In order to find the natural frequency of the sitting surface, excitation was generated by hitting the surface of the structure with a rubber hammer and measuring the forces output by the strain gauge. Since a system subjected to the sudden application of a force has a response at its natural frequency, the transient response of the strain gauge was used to obtain the natural frequency. The frequency of the signal was measured by applying a Fast Fourier Transform (FFT) to the output data of the force transducers. In order to ensure the accuracy of the measurements [19], the sampling frequency was set at 600 Hz. No numerical filter was used in this dynamic calibration. This test also allowed us to determine the maximal amplification of vibration by the instrumented chair, based on its damping. Knowing that when a vibrating system is affected by damping, the amplitude of the oscillations decreases with time, the decay of the force amplitude was used to estimate the damping factor (ζ). When the frequency of excitation (ω_i) approaches the natural frequency (ω_n), the force measured by the transducer (Fm_i) is higher than the excitation force (Fc_i). Since vibration dampers (sheets of neoprene) were used in the platform, we opted for a viscously damped model. According to Thomson [20], the maximum ratio of the measured force to the excitation force occurs at natural frequency with a magnitude of:

$$\left.\frac{\mathrm{Fm}_i}{\mathrm{Fc}_i}\right|_{\omega=\omega_n} = \left.\frac{1}{\sqrt{\left[1-\left(\frac{\omega_i}{\omega_n}\right)^2\right]^2+\left[2\zeta\left(\frac{\omega_i}{\omega_n}\right)\right]^2}}\right|_{\omega=\omega_n} = \frac{1}{2\zeta} \qquad (1)$$

This equation suggests that the maximum amplification is related only to the damping factor ζ.

Since the amplification of force and/or moments is an important source of errors when using inverse dynamic models, it is important to assess these characteristics of the instrumented chair to avoid taking measurements in conditions close to its natural frequency.

2.3 Testing

2.3.1 Dynamic verification test

The frequency content of the sitting task was analyzed. For this test, a person weighting 113 kg was asked to sit on the chair at natural speed with both arms crossed. The subject was instructed to keep both heels in touch with the ground and not to move his feet between trials. Marks on the ground and on the thighs were used to ensure that the subject kept a constant position on the chair. Before each trial, the evaluator made sure the subject was well centered on the chair. Eight trials were analyzed with unfiltered forces sampled at 600 Hz. Since the signal was not periodic, the derivative of the resultant force was analyzed. This approach eliminated the boundary difficulties inherent in the FFT technique and allowed the significant part of the signal to be identified by removing the constant part. Also, since the force variation is faster in the sitting than in the rising phase, only the former was analyzed. The time derivative of the resultant force while the person was sitting was analyzed using a FFT from the MatLab software. The results were integrated to obtain the frequency range containing 90% of the spectrum power.

2.3.2 Sampling corrections

The aliasing effect is a type of distortion that occurs when digitally recording high frequencies with a low sample rate. In that situation, the high-frequency signal components take on the identity of a low-frequency signal [19]. This effect does not occur if all signals with frequencies higher than the Nyquist frequency are removed from the input signal before they are sampled. These vibrations should be filtered before sampling the signal from the platform. The sampling frequency was set at 600 Hz and the signal was filtered with a 10-Hz Butterworth filter (except for the FFT analysis) then sampled again at 60 Hz to match the kinematic data. A triggering signal was used to start the kinematic and kinetic recording devices simultaneously.

2.3.3 SitTS and StandTS trials in a healthy male subject

The instrumented chair was also used to assess the net joint moments at both hips during rising and sitting down trials performed spontaneously by a healthy male subject (age 55 years, mass 87.5 kg; height 170 cm). The participant sat on the chair, centered, with each thigh and foot on one force plate. Then, with both arms folded across the chest, he was asked to stand up, to remain standing for approximately 5 s and then to sit down without moving his feet. The seat of the instrumented chair was set at his leg length. Trials at natural and slow speeds were recorded under three foot positions: (1) Spontaneous: no instructions given on the initial foot position, (2) symmetrical: both feet placed at 15° of dorsiflexion, (3) asymmetrical with the left foot placed behind the right foot. The position of the subject was controlled at each trial as described previously. Overall, 12 trials were performed and retained for analysis.

For each trial, six distinct events, three for each task, were identified. For the SitTS, these events were onset of the task, the transition point that corresponded to almost similar vertical forces under the foot and the thigh, and seat-off. Events for the StandTS task were seat-on, transition and end of the task. Seat-off and seat-on events are the points where the subject leaves the seat with the right thigh and touches the seat with the right thigh, respectively. The beginning of the SitTS and the end of the StandTS were defined respectively as the first and last perceptible change of the vertical or anterior–posterior force (feet or thigh). The time of occurrence of these six events was used in a subsequent program to determine the corresponding hip moments and forces on both sides.

2.3.4 Estimation of hip joint moments

The previously described optoelectronic (Optotrak 3020) system was used to record the kinematic data. The pose of the feet, legs, thighs, pelvis, trunk and head was computed during each task condition. In addition, specific anatomical parts of the feet, shanks, thighs and pelvis were digitized with an Optotrak 6-Marker probe. Kinematic data were filtered with a fourth order Butterworth, zero lag filter, with a cut-off frequency of 6 Hz. The net joint moments at the hip were estimated using an inverse dynamic approach [21] performed with Kingait3 software (Mishac Kinetics, Waterloo, Canada). The hip moments around the x, y and z-axes corresponded respectively to abduction–adduction, internal–external rotation and flexion-extension. In order to appreciate the errors generated when neglecting the forces produced at the seat, the hip joint moments on the left and right sides were recomputed with these components removed from the inverse dynamics approach. In addition to quantifying these errors for the six events, the right-left difference in the hip net moment was also examined. Paired t tests allowed comparison of the data. A preliminary investigation of the relation between hip moments at seat-off (or seat-on) and at transition for both tasks was also performed using simple Pearson correlation coefficients. Using the data at "transition" we also investigated the level of association between the left–right force differences at the feet with those at the thighs as well as with the left–right differences in the hip extension moment.

3 Results

3.1 Calibration

The static calibration tests performed on a total of 72 samples showed that the maximal vertical error was less than 2% of the full-scale output of 726 N for both sitting surfaces of the seat. For the quasi-static calibration tests in the horizontal direction, a maximal horizontal error of 2% of the full-scale output of 164 N over 2,400 samples was found. The determination of the COP position showed a RMS error of 5 mm with a maximum of 9 mm. A total of 9,600 samples were used to obtain these values.

The natural frequency (mean $\pm$ SD) and damping factor were respectively 14 ± 2 Hz and 0.2. The maximum amplification was therefore 2.5 at natural frequency. The power spectrum of the derivative of the resultant force was obtained using eight sitting trials performed by a person weighting 113 kg. Integration of this FFT analysis gave more than 90% of the power spectrum at frequencies lower than 3 Hz. These experimental frequencies are thus around five times lower than the critical value of the natural frequency.

3.2 Testing

Figure 2 shows the reaction forces at the thighs and feet obtained for the subject performing a rising movement followed by a sitting-down one for the three-foot positions. For the vertical forces, there was a simultaneous decrease and increase of the force under the thigh and foot, respectively. This characterizes very well the progressive shift of the weight from the thighs to the feet during the rising task and from the feet to the thighs for the sitting-down task. As for the antero-posterior (A–P) forces, they were positive at the thighs (forward direction) whereas a negative sign was observed at the foot. The medio-lateral (M–L) forces were positive on the left side at both the thigh and the feet and negative on the right side revealing a medial (inward) component for both sides. Visual observation of the profiles of the reaction forces revealed an influence of the foot position condition on the right-left distribution of the forces. Even for the symmetrical foot position, right–left force differences at the thighs were observed. For the SitTS, regardless of the events, the maximal absolute mean $\pm$ SD differences between sides were 15 N $\pm$ 10, 64 N $\pm$ 20 and 10 $\pm$ 5 N for the A–P,

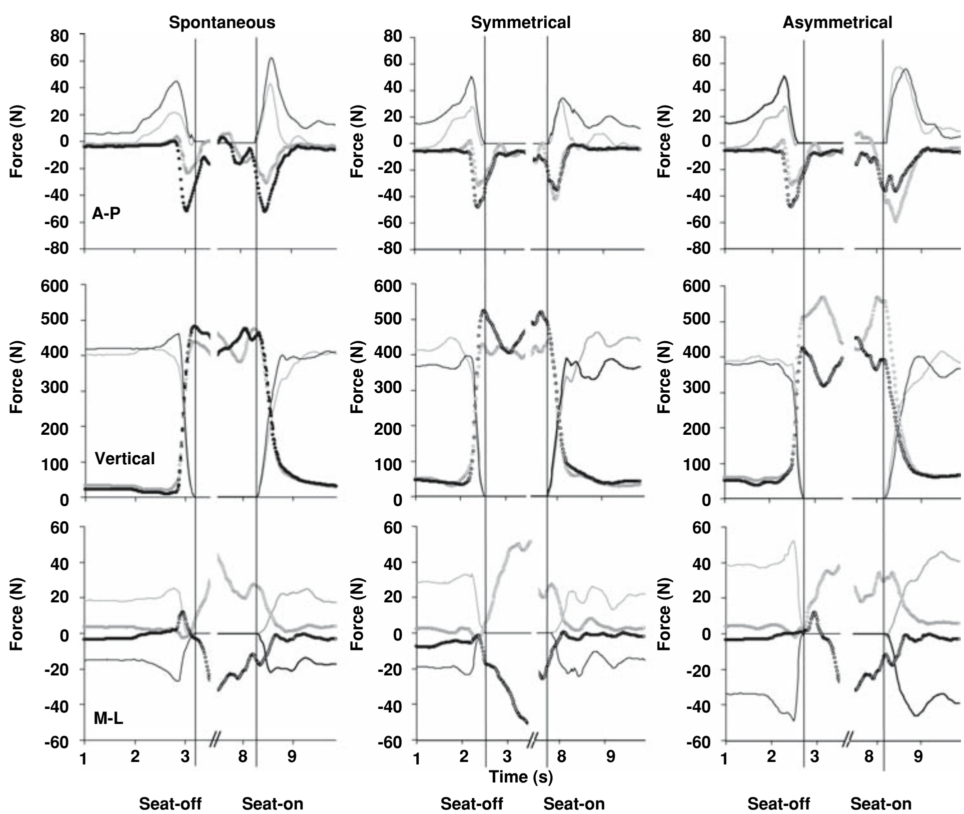

Fig. 2 Time data for the vertical, antero-posterior (*A–P*) and medio-lateral (*M–L*) reaction forces at the thighs and feet for the three foot positions. The healthy participant was asked to stand up, to remain standing approximately 5 s and then to sit down. The standing period was truncated for clarity. The seat-off and seat-on events are identified. The solid black line refers to the right thigh, the dashed black line is for the right foot, the solid and dashed grey lines refer respectively to the left thigh and left foot

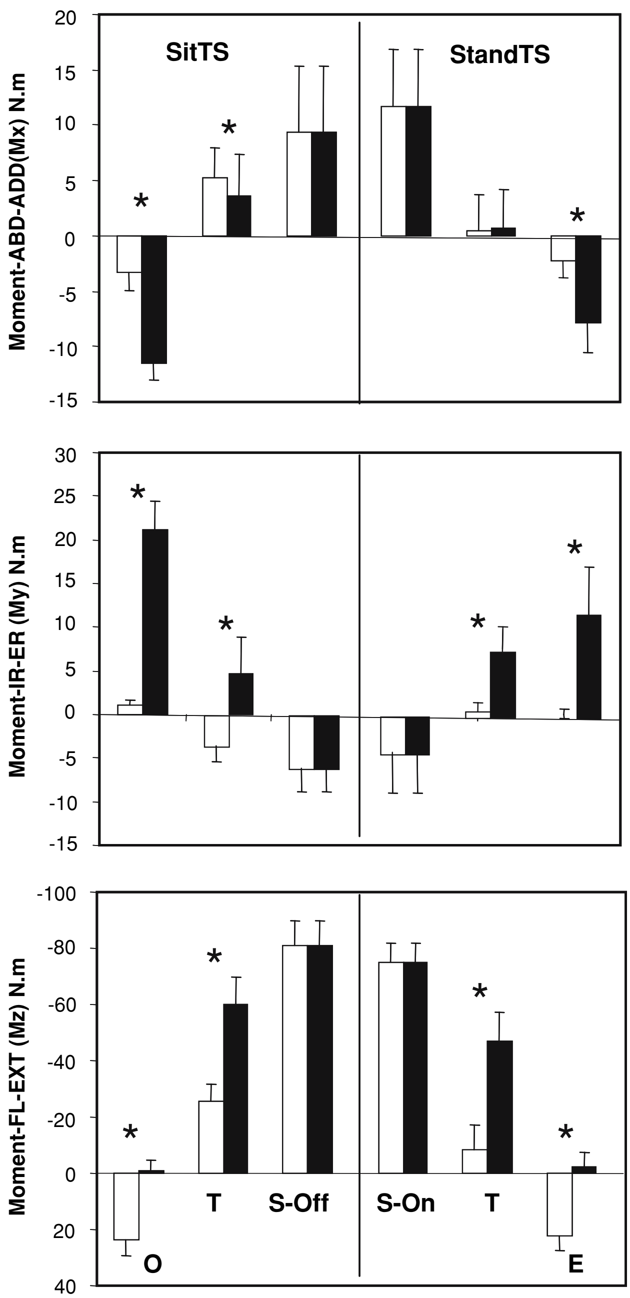

Fig. 3 Mean (±SD) hip net joint moments (frontal, transverse and sagittal) on the right side for the six events. The moments are shown for two calculations: considering the force and moment components under the thigh (*dark bars*) and not considering the thigh data (*white bars*). Adduction, internal (inwards) rotation and flexion moment directions are positive

vertical and M–L force components, respectively. Corresponding values for the StandTS tasks were 13 ± 5, 73 ± 50 and 10 N ± 4.

Significant differences were found for the hip net joint moment in the frontal (abduction–adduction), transverse (internal–external) and sagittal (flexion–extension) planes computed with (first method) and without (second method) consideration for the forces exerted on the sitting surface in the inverse dynamic method (Fig. 3). For the three hip moments, the two methods not only changed the magnitude of the moments, but also led to a different interpretation of the results. For example, in the sagittal plane, the first method (with seat) indicated almost no moment in the sitting position whereas the second method revealed a hip flexion moment. On the right side, the mean differences in the sagittal hip joint moment between the two methods reached 34.2 ± 10.4 and 38.8 ± 12.5 Nm for the SitTS and StandTS tasks, respectively. Corresponding values for the left-right differences were 20 ± 9 and 8 ± 12 Nm. As expected at seat-off or seat-on, no difference was observed between the two methods.

The Pearson correlation coefficients used to determine whether the hip moments at transition could be predicted by the hip moments at seat-on (or seat-off) revealed values of 0.48, 0.76 and 0.23 for frontal, transverse and sagittal moments, respectively. Values over 0.50 were significant at the 0.5 level of significance. Lastly, an association between the left-right differences in the force at the feet and at the thighs (A–P: $r = 0.66$; vertical: $r = 0.85$; M–L: 0.75) was found. However, the left–right differences in A–P and vertical directions at the feet at seat-on (or seat-off) were not associated with the left–right sagittal moment differences at the hip at transition and accounted for less than 8% of the variance in the data, even when both force components (A–P and vertical) were used together.

4 Discussion and conclusion

This paper describes the design, technical characteristics and first results of an adjustable instrumented chair with a sitting surface. The seat includes a force platform assembly suitable for measuring the magnitude, position and direction of the force under each thigh while sitting on or rising from the chair.

The static and quasi-static tests showed an acceptable 2% error level on the measured forces [3]. The COP test gives an acceptable error of 5 mm RMS, which is similar to that found with commercially available simple force plates. This chair can therefore be used for quasi-static experiments such as weight distribution in the sitting position or for a slow reaching task.

The dynamic test gave a natural frequency of 14 Hz. This is the weakest characteristic of the new chair and needs to be addressed. As usually stated, the natural frequency of a measuring device should be at least five times the frequency level contained in the desired signal. Consequently, for an error level below 4% (according to Eq. 1), the signal should not contain significant frequencies higher than 3 Hz. Since the results of the integration of the FFT analysis obtained from the trials performed by the person weighting 113 kg revealed that more than 90% of the power spectrum is obtained at frequencies below 3 Hz, the results of the dynamic tests performed are acceptable and the chair can therefore be used to assess the SitTS and StandTS tasks.

The new instrumented chair allows measurements of the force and moment components under each thigh to be measured when the seated subject initiates the rising task. Thus, the net joint moment at the hip could be computed throughout the task and not only after seat-off (SitTS) or before seat-on (StandTS). Comparison of the hip joint moment values computed with and without considering the forces under the thighs revealed significant differences in the three net moments at events before the seat-off and after the seat-on, for the SitTS and StandTS, respectively. Moreover, the moment values at seat-off (or seat-on) cannot be used to estimate those at the transition, except for the abduction-adduction moment. It should be noted that the differences between the two methods did not affect the peak values of the hip moment data presented because they occurred after or before the subject made contact with the seat. However, this does not preclude the possibility that the peak will never be affected, since the occurrence could potentially be changed by factors such as the speed of the task and the trunk position [2, 4]. Moreover, it is noteworthy that, since the inertial parameters of subjects differed, they could have a different influence on the force and moment components during the SitTS and StandTS tasks. Future studies will need to clarify how the characteristics of the subjects and their strategies influence the results.

The preliminary analysis revealed asymmetrical forces under the thigh and foot between each side, even for the symmetrical foot position. In addition, despite the association found between the side difference in the forces at the feet and at the thighs, the side differences at the feet were not useful for estimating the sagittal hip moment differences. Our first conclusion was that bilateral symmetry in the net joint moments cannot be assumed and that actually there is no easy way to determine this level of asymmetry. Future studies will need to address the effects of different variables such as the horizontal and vertical force components as well as the trunk kinematics in a large group of subjects in order to determine which of these three components has the greatest impact on the hip moments before seat-off or after seat-on. This information could then guide investigators who do not have the resources or who cannot implement a similar measurement system to use an alternative approach. Future studies with the chair would provide additional information on these aspects.

Overall, the results indicate that the chair can be used to assess dynamic tasks such as rising and sitting down. It is currently proving useful for assessing the biomechanics of rising from and sitting down on a chair among healthy and hemiparetic subjects.

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