A NEW DESIGN OF A MULTI-MOMENT-CHAIR SYSTEM

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Abstract
An apparatus has been developed that measures isometrically the 14 lower limb joint moments corresponding to the degrees of freedom (DOF) of the hips, knees, and ankles. The main constructive features are that i) leg posture can be varied for many degrees of freedom and within a large angular range, ii) posture adjustments can be performed very easily and quickly, iii) the chair can be adapted to subjects with different anthropology, and iv) it is easy to get in and out. All joint moment errors have been calculated to be less than 7% of the peak moment responses, which is considered sufficiently accurate for the proposed application. The system will be used for the development of model-based closed-loop controlled neuroprostheses.

Introduction
There are several reasons, why the measurement of isometric joint moments is so important for the development and application of neuroprostheses for spinal cord injured (SCI) patients. First, the state of muscle function or atrophy can be assessed qualitatively in patients with complete or incomplete lesions [1]. Second, the placement and stimulation levels between different channels of implanted or surface electrodes can be optimised and their functionality in terms of maximum joint moment output can be tested [2]. Third, quantitative information about maximum isometric joint moments as function of joint angles are required for the model-based control of neuroprostheses [3], [4].

For the development of a gait neuroprosthesis an apparatus has been designed and built that measures simultaneously 14 isometric leg joint moments corresponding to the degrees of freedom (DOF) of the hips, knees, and ankles. The construction is based on an existing technical concept [2]. The new version presented here has been modified in such way that the adjustment of joint angles has been improved. Furthermore, it allows the variation of additional joint angles (hip abduction, ankle abduction and inversion), which may be of importance when studying the angle-dependent effects for some movements and pathologies.

Additional requirements are: large angular joint ranges, possible adaptation to subjects with different anthropology, high accuracy, high stiffness/little oscillations, safety, easy to get in and out, etc.

Design
The human lower limb has seven principal DOF - three at the hip, one at the knee and three at the ankle joint. Associated with each of these DOF is an angle-dependent joint moment. These are calculated from measured restraint force-moments at the ankle and proximal to the knee.

Fig. 1: Multi-moment-chair design. Depending on the operating mode, different knee supports are used with the slides locked or free to move.

The apparatus consists of three main components that fix the lower limbs and pelvis of the subject (Figs. 1 and 2): the seat with backrest, the two foot supports, and the two knee supports. Different joint angles are accommodated by inclining the backrest, or lower leg bars, rotating the leg frames in the horizontal and adjusting the plantarflexion, abduction, and inversion angles of the foot supports. Thus, 12 DOF - all principal joint axes except internal/external hip rotation - can be adjusted in a range that is similar to the maximum joint angular ranges in humans (Table 1).

External technical joint axes correspond with the internal anatomical axes to allow correct determination...
of static joint moments as well as easy - and thus quick - angular adjustments without causing passive tension while moving the joints. This is enhanced, because unbolting and arresting of the technical axes can be done by small levers, thus, avoiding the use of tools.

<table>
<thead>
<tr>
<th>Degree of Freedom, DOF</th>
<th>Human Min. ... Max.</th>
<th>Chair Min./Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip Flexion</td>
<td>-15° ... 140°</td>
<td>-20° ... 130°</td>
</tr>
<tr>
<td>Hip Abduction</td>
<td>-30° ... 45°</td>
<td>-10° ... 80°</td>
</tr>
<tr>
<td>Hip External Rotation</td>
<td>-45° ... 45°</td>
<td>Not adjustable</td>
</tr>
<tr>
<td>Knee Flexion</td>
<td>-10° ... 150°</td>
<td>-10° ... 130°</td>
</tr>
<tr>
<td>Ankle Plantarflexion</td>
<td>-30° ... 50°</td>
<td>-40° ... 130°</td>
</tr>
<tr>
<td>Ankle Abduction</td>
<td>-20° ... 20°</td>
<td>-50° ... 50°</td>
</tr>
<tr>
<td>Ankle Inversion</td>
<td>-20° ... 20°</td>
<td>-20° ... 20°</td>
</tr>
</tbody>
</table>

Table 1: Joint angular ranges in humans [5], [6] and the multi-moment-chair, assuming orthogonal axes at each joint.

The chair contains very stiff components not only to avoid damage of mechanical components due to overload but also to minimise bending and oscillation effects. The positions of all seven axes can by adjusted in order to adapt the chair dimensions to subjects with different anthropometry and body height varying between 1.3 and 2.0 m.

Fig. 2: Photograph of the multi-moment-chair system

Function

The large range of motion of the left and right leg frames (up to 80° hip abduction) makes it possible to "open" the chair so that it is easy to approach even with a wheelchair and lift the patient onto the cushioned seat (this is normally done by the staff). The subject sits with thighs horizontal. Straps are used to fix the pelvis at the seat as well as the feet at the foot supports. At the foot support a 6 DOF strain-gauge-based force-torque sensor (ISA F/T, from ATI Industrial Automation, Inc.) records the foot reactions.

The multi-moment-chair operates in either of two modes, "seated" or "extended", for which different knee supports are used [2]. In "seated mode", with the foot supports locked, the only remaining freedom of movement would be lateral movement at the knees. This is restrained by knee supports that allow vertical movement (see Fig. 1, right leg frame). The lateral restraint forces are measured by single DOF strain-gauge-based load cells (Soemer Meßtechnik GmbH, sensor type 3510) at each leg. These sensors are insensitive to other DOF.

In order to obviate the singularity at full knee extension, the chair has to operate in "extended mode", when the knees are adjusted at angles close to full extension [2]. In this mode the foot supports are free to slide longitudinally along the lower leg bar. This is fulfilled by low-friction linear guides (FMS, Bosch) that are locked during the other mode. In the extended mode restraints are required at the knees to fix the leg position, both laterally and vertically by using other knee supports (Fig. 1 left leg frame, Fig. 3). Lateral and vertical forces are measured by two strain-gauge-based single DOF load cells (Soemer Meßtechnik,). Ball-and-socket joints are used to reduce influence of cross talk due to torque transmission (Fig. 3).

Fig. 3. Knee support for the extended mode.

For each leg seven joint moments need to be calculated based on seven external force/torque measurements from the sensors. We assume that the axes at each joint are orthogonal. The ankle is treated as one joint between the malleoli. By restraining the legs so that no, or in practice little, movement occurs, the legs reach static equilibrium. Then, the internal joint moments can be calculated as functions of joint angles (posture), limb lengths (anthropometry), and the forces and torques measured by the sensors [2].
Error analysis

An error analysis was performed to assess how the measured length, angle, force, and torque errors affect the calculated joint moment values. The maximum joint moment errors were calculated by partial differentiation of the joint moment expressions obtained from the static equilibrium equations [2]. Force/torque sensor errors (standard deviations) were taken from the sensor data sheets. Errors of limb lengths and joint angles were estimated in [2]. Most critical is the knee joint angle, since the knee moves slightly during stimulation (strong extending moments pushes the pelvis back). Assuming a knee angle error of 3°, the maximum relative errors obtained by this analysis were estimated to be less than 7% for all joint moments in both the extended and seated mode.

Preliminary Measurements

Test measurements were performed in one healthy subject. A Microstim8 stimulator (Krauth + Timmermann) delivered bi-phasic rectangular stimulation pulses. The quadriceps femoris, gluteus maximus, tibialis anterior, and gastrocnemius muscles of the left leg were stimulated with surface electrodes consecutively. Frequency and pulse width were held constant at 20 Hz and 300 µs, respectively, whereas current amplitude was modulated between 0 and 50 mA by linearly increasing and decreasing ramps.

Fig. 4 shows the calculated joint flexion moments at different joints, when stimulating muscles in the seated mode. No significant mechanical oscillations of the construction appeared during the recordings.

Discussion

An apparatus has been developed that measures the 14 principal lower limb joint moments, with the legs fixed in a wide range of different postures. The chair can be "opened" so that it is easy to get in and out. Furthermore, it can be adapted to subjects with varying anthropometry.

An outstanding feature of the multi-moment-chair is that external technical joint axes correspond with the internal anatomical axes. Compared to a former version [2], this exoskeleton-type solution enables simpler and faster changes of posture, while avoiding internal passive tension during joint angular adjustments. This allows fast measurement sessions, minimising the risk of pressure sores and making the investigations less cumbersome and more patient friendly.

On the other hand, in this exoskeleton-type construction high bending moments can be gained in the leg bar, causing it to oscillate. However, it has been shown that these oscillations are small in amplitude and do not affect the joint moment data.

The error analysis of the joint moments suggests that during stimulation the errors are small enough to enable useful measurements. Experimental validation of the accuracy of the multi-moment-chair has still to be done. This is, however, challenging, because internal joint moments produced in living subjects are difficult to determine. A possible solution would be the validation with a dummy, in which known joint moments can be generated and measured by the apparatus.

References


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