Journal of Medical Engineering & Technology, Volume 28, Number 2, (March/April 2004), pages 74–80

Standing-up robot: an assistive rehabilitative device for training and assessment

R. Kamnik* and T. Bajd

University of Ljubljana, Faculty of Electrical Engineering, Tržaška 25, 1000 Ljubljana, Slovenia

In this paper a robotic assistive device is presented, aimed at assisting physically impaired individuals when rising from a sitting to a standing position. The robotic device is designed as a three degrees of freedom (3-DOF) mechanism supporting the subject under the buttocks. The device is driven by an electrohydraulic servosystem capable of operating in multiple control modes. It is instrumented with a sensory system providing information about the standing-up parameters. Evaluation of the standing up assistive device was accomplished in robot-supported rising trials of a paraplegic subject. The experiments demonstrated that stable risings in different standing–up manoeuvres were achieved. The measurement results revealed the role of the arm support and the support of the artificially evoked moments in the paralysed lower extremities during rising. The results show that the device can be used efficiently for training and evaluation of standing up manoeuvres.

Introduction

Rising from chairs is a common but demanding activity of daily living. Physically impaired persons and the elderly often have difficulty when rising to a standing position. There are many reasons that cause rising difficulty, such as pain, muscle weakness, partial loss of motion control or physical deformity of the joint structures. Consequently, individuals experiencing rising difficulties have problems living independently, while their prolonged immobilization results in physiological problems. Regular standing up and standing activity should ameliorate some of the problems.

To compensate for the lack of lifting forces, people with disabilities usually develop an adapted approach to standing up with an additional aid often utilized. For example, arm supports such as walker frames, parallel bars, simple stationary standing frames or chair arm rests are commonly used. It has been shown that when healthy subjects stand up, use of an arm support substantially reduces the net moments in the lower extremity joints [1, 2]. However, transfer of bodyweight to the upper extremities during rising requires a fit upper body. A person practising fully arm-supported rising risks later complications of the upper extremity joints [3]. Raising the seat height also eases the sit-to-stand (STS) transfer [4]. Hence, various mechanical constructions have been designed to act as lifting chairs. They exert a lifting force to the occupant while adjusting the seat height during rising. These mechanisms are typically based upon passive principles, exploiting spring or counterweight forces [5, 6]. In addition, standing up can also be performed with the help of functional electrical stimulation (FES) [7]. FES is a convenient method for selected persons suffering loss of motor control due to spinal cord injury or stroke. Motor functions are recovered by invoking muscle contractions of the paralysed limbs with the help of electrical pulses. It has been shown that standing up can be achieved with a minimum of two FES channels delivered to both knee extensors through two pairs of large surface electrodes [8]. FES-supported standing up in paraplegia has been thoroughly studied [9, 10]. These studies demonstrated that there are improvements to be made in the intensity, timing, and control of FES. To this end, novel FES control systems are being investigated [11–13].

When training a physically impaired subject in the task of standing up, the trainee needs to be, for numerous repetitions, restrained to a position trajectory and adequately supported to maintain postural stability. Furthermore, investigating new approaches to standing up requires feedback information to evaluate the effects of training. Training in standing up is usually performed by the manual support of physiotherapists in rehabilitation institutions. To relieve physiotherapists from this heavy burden and to assure higher repeatability, various mechanical aids can be employed. In a study of rising [14] the 'Thigh exerciser' was used to support the rising subject's back. The device consists of a back support with a movable sled which is held by the hands of the subject. Riener *et al.* [11] constructed a seesaw-like mechanical system supporting the subject under the buttocks. The mechanism was successfully used in experiments with a new FES control system. Both mechanical systems described are counterweight-based passive devices intended to aid the rising subject and assure stability. However, both of the devices neither provide feedback information about the rising process nor have the capability of motion trajectory programming.

In this paper, a novel standing-up robotic assistive device is presented. The robot is constructed as multipurpose device for human motion augmentation

*Author for correspondence; e-mail: roman.kamnik@robo.fe.uni-lj.si

Journal of Medical Engineering & Technology
ISSN 0309-1902 print/ISSN 1464-522X online © 2004 Taylor & Francis Ltd
http://www.tandf.co.uk/journals
DOI: 10.1080/0309190032000112306

during rising. This paper is organized as follows. In the second section, the mechanical design of the prototype device and its control system are described. The third section presents the preliminary results of the device evaluation in the robotic assisted standing up of a paraplegic subject. In conclusion, the planned improvements of the proposed robot technology are discussed.

Mechanical configuration and control system of the standing up robotics assistive device

In the standing up manoeuvre, the ultimate goal is to bring the upper body from an initial sitting position to the final standing position. During the STS transfer, the upper body can be considered to be restricted to three degrees of freedom (DOF) of motion. It moves vertically and horizontally in the sagittal plane, while changing its orientation in the antero-posterior direction. According to Donaldson and Yu [12] the orientation of the upper body in a completely paralysed spinal cord injured subject can be controlled only by the upper extremities. Thus, it can be reasonably assumed that the majority of subjects who are unable to stand up (the elderly, people with paraplegia or even some tetraplegic patients) will be able to control their upper body orientation by means of an arm support. In this respect, an active mechanical system supporting the rising subject under the buttocks and in this way imposing the subject's hip trajectory meets the requirements for robot-supported standing up.

The novel standing-up robot device, developed according to the directions above, is presented in figure 1. The robot device is a 3-DOF mechanism which, in order to support the subject, resembles half of a seesaw. The subject sits on a standard bike seat mounted at the robot end-effector. The robot configuration enables an arbitrary seat motion restricted to the subject's sagittal plane. Positioning of the end-effector is accomplished by movement of the two robot segments. The first segment rotates around its axis on a robot base, while the second translational segment moves longitudinally along the first. Both segments are driven by linear hydraulic actuators. At the robot end-effector the orientational mechanism is mounted assuring horizontal seat orientation in any robot position. Constant seat orientation is maintained by a passive hydraulic bilateral mechanism. This consists of two cylinders, master and slave, with the master piston coupled to the driving first robot segment. Each of the two passages on the cylinders are connected in parallel to the other cylinder through flexible tubes. The displacement of the piston stroke in a master cylinder causes the corresponding displacement of the piston stroke in a slave cylinder. The seat is thus rotated according to the motion of the first robot segment and the horizontal seat orientation is maintained. Under the seat mechanism the six-axis JR3 45E15A force/torque sensor (JR3, Woodland, CA, USA) is mounted in order to assess the contact force between the robot end-point and the raising subject. In this manner the subject–machine interaction and hence the robot assistance to the standing up process can be assessed online. Optionally, the pressure values in cylinder chambers can be acquired via two VDO 7349.080 pressure sensors (VDO Industrie Messtechnik, Frankfurt/Main, Germany).

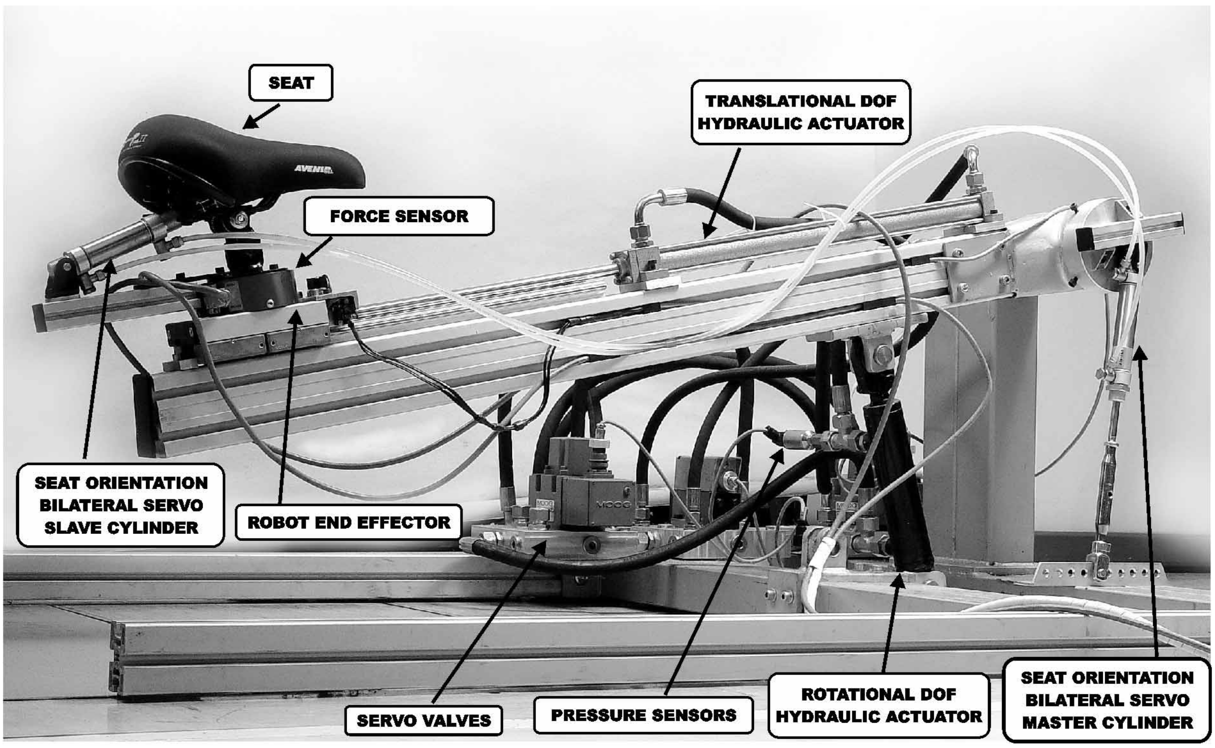

Figure 1. Standing-up robotic supportive device.

The standing-up robot mechanism is driven by the electrohydraulic servosystem presented in figure 2. The system is powered by a hydraulic pump providing the pressure of 50 bars and the hydraulic current of 1 $l\,s^{-1}$. The pump performances allow the maximal speed of the robot end-effector up to 2 $m\ s^{-1}$. The current driven Moog 062-234 servovalve (Moog, New York, USA) is used to control the pressure difference applied to the linear hydraulic cylinder driving the translating link. Furthermore, two Moog D641-3 servovalves with incorporated electronics form a hydraulic arrangement which drives the rotating link. This arrangement enables the individual chamber pressure control in the hydraulic cylinder [15]. In this way, two operational modes are provided for the rotating link. In the position control mode, the system accomplishes the desired motion trajectory regardless of the interaction between the subject and the robot. While in the force control mode, an explicit control of interaction force is possible.

The hydraulic servosystem is controlled by a computer system built upon a 1 GHz PC Pentium III platform (see figure 2. On the platform, the RTLinux v.3.1 real-time operating system runs at a constant sampling rate of 2 KHz. Two PCI interface boards are used to interface the external hardware. The PCI-DDA08 board (Measurement Computing, Middleboro, MA, USA) acquires the analog force and pressure signals, and reads the joint positions via digital inputs. The joint positions are assessed with the help of rotational incremental encoders interfaced via HCTL 2016 integrated circuits (Motorola, Anaheim, CA, USA). Another Measurement Computing board type D/A PCI-DAS1002 is employed

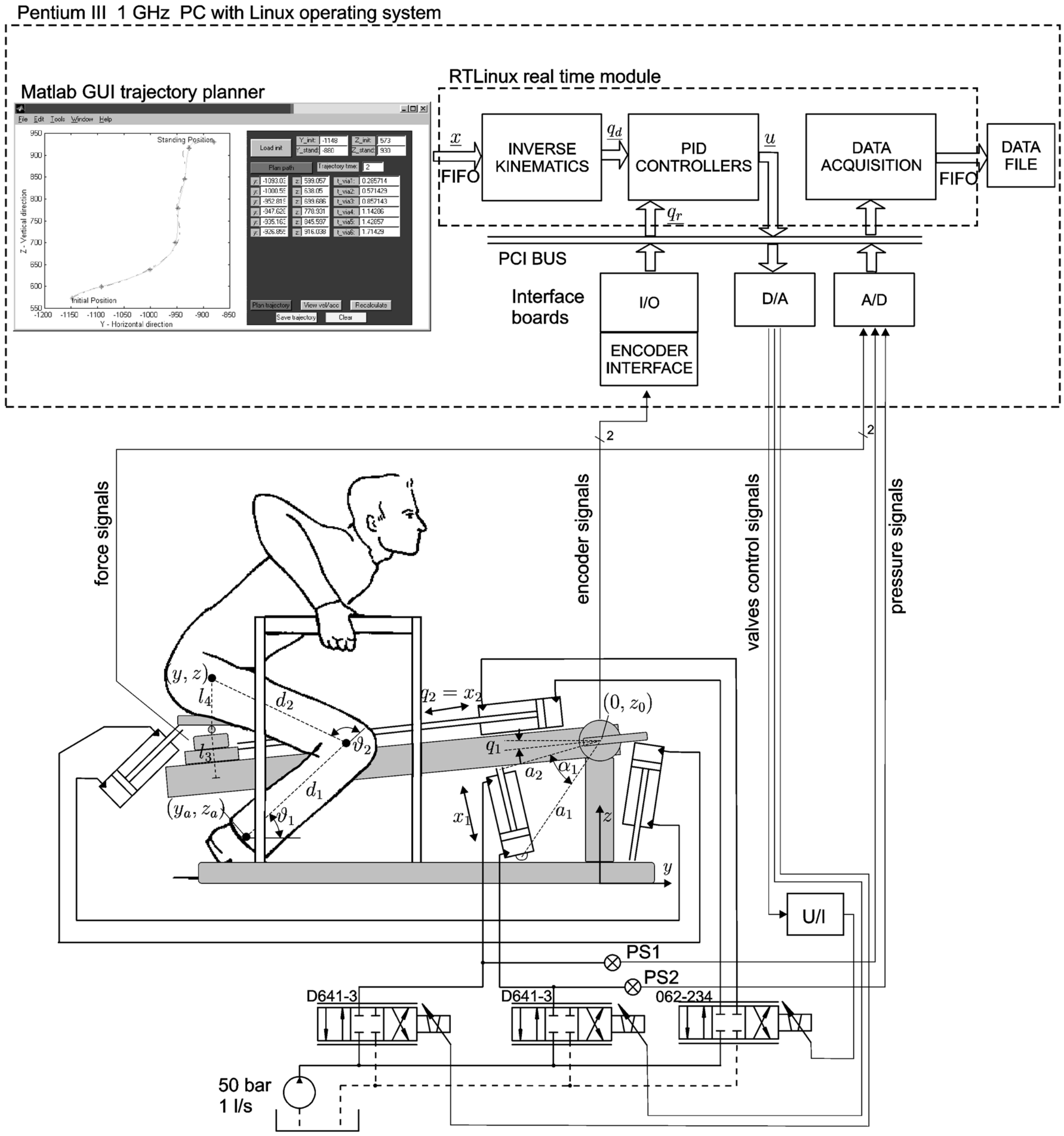

Figure 2. Control system of the standing up robotic assistive device: hydraulic circuit diagram, trajectory planner and real-time controller.

to drive the hydraulic servovalves applying the output voltage in a range of $\pm$ 10 *V*.

In the position mode of operation, the control objective is to guide the robot end-effector along the predetermined path specified in terms of velocity and/or acceleration at each point. When the rising subject is supported by the standing up robot, the seat motion trajectory coincides with the motion trajectory of hip joints. The hip joint trajectory (acquired, for example, during a 'reference' rising by an optical measurement system) can therefore be used as the reference for the robot controller. As an option, a graphic interface was built to ease the robot trajectory planning for the user. The trajectory planner is built in a Matlab GUI environment (The MathWorks, Natick, MA, USA) and enables a simple indication of the start, end and intermediate path points using the mouse. Along the consecutive points, the cubic spline interpolation is calculated. In the user interface the path velocity profile planner is incorporated, applying the desired velocity profile. The velocity profile is freely programmable and is in principle constrained only by robot dynamics. Moreover, the free programming option permits planning of the robot end-point trajectory with the objective of achieving a constant angular velocity of the knee extension or ankle dorsiflexion. Specifically, if we assume that the ankle position (y_a, z_a) is known and remain constant during standing up, the inverse kinematic solution of the lower extremity geometrical model:

$$\begin{aligned} y &= y_a + d_1 \cos \vartheta_1 + d_2 \cos(\vartheta_1 + \vartheta_2) \\ z &= z_a + d_1 \sin \vartheta_1 + d_2 \sin(\vartheta_1 + \vartheta_2) \end{aligned} \tag{1}$$

determines the knee and ankle joint paths as:

$$\vartheta_2 = \arctan \frac{\sin \vartheta_2}{\cos \vartheta_2} \tag{2}$$

$$\vartheta_1 = \arctan \frac{\sin \vartheta_1}{\cos \vartheta_1} \tag{3}$$

where

$$\begin{aligned} \cos \vartheta_2 &= \frac{(y - y_a)^2 + (z - z_a)^2 - d_1^2 - d_2^2}{2 d_1 d_2} \\ \sin \vartheta_2 &= \sqrt{1 - \cos^2 \vartheta_2} \\ \cos \vartheta_1 &= \frac{y(d_1 + d_2 \cos \vartheta_2) + z\, d_2 \sin \vartheta_2}{y^2 + z^2} \\ \sin \vartheta_1 &= \frac{z(d_1 + d_2 \cos \vartheta_2) - y\, d_2 \sin \vartheta_2}{y^2 + z^2} \end{aligned} \tag{4}$$

Along the path determined according to equations (2–4), the trapezoidal velocity profile can be applied, indirectly defining the robot-end point motion velocity. In this way, the isokinetic conditions, needed for isokinetic training or movement analysis, can be established.

When planned, the robot end-point trajectory is loaded into the FIFO mechanism (first in, first out Unix file system) from where it is fed to the controller input. In the controller, the robot inverse kinematic solution yields the robot joint coordinates:

$$\begin{aligned} q_1 &= \arctan \frac{\sin q_1}{\cos q_1} \\ q_2 &= \frac{l_4 + l_3 \sin q_1 + z_0 - z}{\sin q_1} \end{aligned} \tag{5}$$

where

$$\begin{aligned} \sin q_1 &= \left(\frac{y^2 + z^2 - (z_0 + l_4)^2 + (q_2 + l_3)^2}{-2(z_0 + l_4)(q_2 + l_3)} \right) \\ \cos q_1 &= \sqrt{1 - \sin^2 q_1} \end{aligned} \tag{6}$$

The robot joint coordinates q_i are related to the linear actuator coordinates x_i through the nonlinear transformation:

$$\begin{aligned} x_1 &= \sqrt{a_1^2 + a_2^2 - 2 a_1 a_2 \cos\left(\frac{\pi}{2} - q_1 - \psi_1 - \psi_2\right)} \\ x_2 &= q_2 \end{aligned} \tag{7}$$

Finally, the PID control law is implemented, minimizing the error between the desired and actual actuator positions and hence assuring the tracking of the desired robot end-point trajectory:

$$\underline{u_i} = \underline{k_p}(\underline{x_r} - \underline{x}) + \underline{k_d}(\underline{\dot{x}_r} - \underline{\dot{x}}) + k_i \int (\underline{x_r} - \underline{x}) \tag{8}$$

Robot-supported standing up of a paraplegic subject

In order to demonstrate the applicability of the robot device in standing up of physically impaired individuals, several experimental standing up trials were performed. In the experiments, a person with paraplegia and long lasting experience in FES usage was involved (subject MT, female, 30 years, 171 *cm*, 75 *kg*, injury level T 4–5, 7 years of FES training). In the experiments, a surface stimulator providing a constant stimulation pattern to the knee extensors was utilized throughout the rising.

Experimental setup

In figure 3 the experimental setup is shown including the robotic assistive device and the arm supportive frame. The forces on the arm support frame were measured by a six-axis JR3 robot wrist sensor (JR3), while the foot reactions were assessed by the AMTI force plate (AMTI, Watertown, MA, USA). Motion of body segments was measured with an Optotrak optical system (Northern Digital, Waterloo, Canada) which measures the 3D positions of active markers (infrared LEDs). Markers were attached to anatomical landmarks at the ankle, knee, hip, pelvis, shoulder, elbow, wrist and head. Assuming that the human body is symmetrical during the standing-up motion, measurements

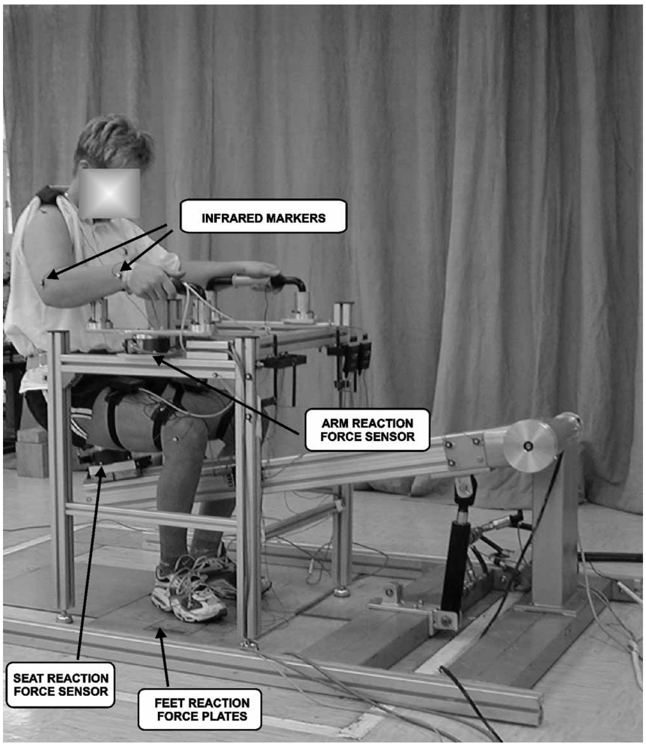

Figure 3. Paraplegic subject and the standing up measurement setup.

were made only for the patient's right side, and were calculated for the left side.

Measurement protocol

The subject was seated on the robot seat with arms resting on arm support frame. The initial height of the seat coincided with the height of a wheelchair. Prior to the measurements, three unsupported standing up trials were performed to relieve spasticity in the paralysed extremities and familiarize the subject with the measuring equipment. In the following unsupported trial, the hip joint trajectory was recorded defining the 'reference' robot end-point trajectory.

The subject was asked to accomplish several robot-supported standing up trials. The trials were accomplished under three different conditions: (a) standing up with the support of the robot device; (b) standing up with the support of the robot device and arms, and (c) standing up with the support of the arms, robot device and FES of the knee extensor muscles. For each standing up approach, the subject was asked to accomplish two preparatory standing up trials and afterwards, four standing up trials which were recorded for data analysis.

The initiation of standing up, i.e. triggering of the robot motion and FES, was left to the subject. Triggering was realized via a push-button mounted on the walker handle. The robot operated in a position control mode ensuring tracking of the reference trajectory.

Data analysis

The data collected from the force sensory systems were used to determine the particular contributions of the arms, stimulated knee extensors, and robot to the bodyweight lifting manoeuvre.

For the purposes of dynamic analysis of STS transfer, a three-dimensional sagittally symmetrical 13-segment dynamic model of the human body was developed. The model embodied feet, shanks, thighs, pelvis, trunk, head, upper arms, lower arms and hands. Each segment had six degrees of freedom in the space and was considered to be a rigid body. The segmental masses, mass centres, and moments of inertia were estimated from anthropometric relationships [16]. Forces and moments acting at the joints were calculated recursively using Newton–Euler inverse dynamic analysis [17].

Results

In figure 4, the results of the kinetic analysis of robot-supported standing up are summarized. The graphs are arranged in three rows which are examples of standing up performed under three different rising regimes. In each row, the graph on the left side presents the ratios of the bodyweight bearing among the robot, voluntarily controlled upper and electrically stimulated paralysed lower extremities. The contributions, expressed as percentages of the total bodyweight, are assessed from the seat, arm and foot reaction force measurements. The graphs on the right side present the forces and moments in the rising subject's body, determined by inverse dynamic analysis. As relevant in rising, the shoulder moment in the sagittal plane, the shoulder vertical force and the knee joint moment are presented.

In figure 4, graphs 1A and 1B illustrate results from a person with paraplegia standing up with no effort of her own. The great majority of the lifting forces were provided by the robot device, which in this case acted like a lifting mechanical aid. Arm supports were used only to the extent of providing upper body lateral and antero–posterior postural stability. This example can serve as a worst-case example when considering the human–robot interaction. It is evident that during rising the seat was loaded with a short peak of 728 N (99% of bodyweight). The peak loading resulted in a pressure of 7.7 $N\ cm^{-2}$ when a seat with a 94 cm^2 support area was used. This short duration loading on the soft-seated bicycle seat may be considered as a safe interaction pressure.

Graphs 2A and 2B of figure 4 show an example of standing up by the robot and arm support. The arm support provided additional lifting force. The robot device provided a significant contribution to the lifting forces at the beginning of the standing up process, while towards the end, when an upright posture was attained, the arms took over a considerable part of the loading. During standing, the robot device assisted in maintaining the upright posture when the subject released her arms.

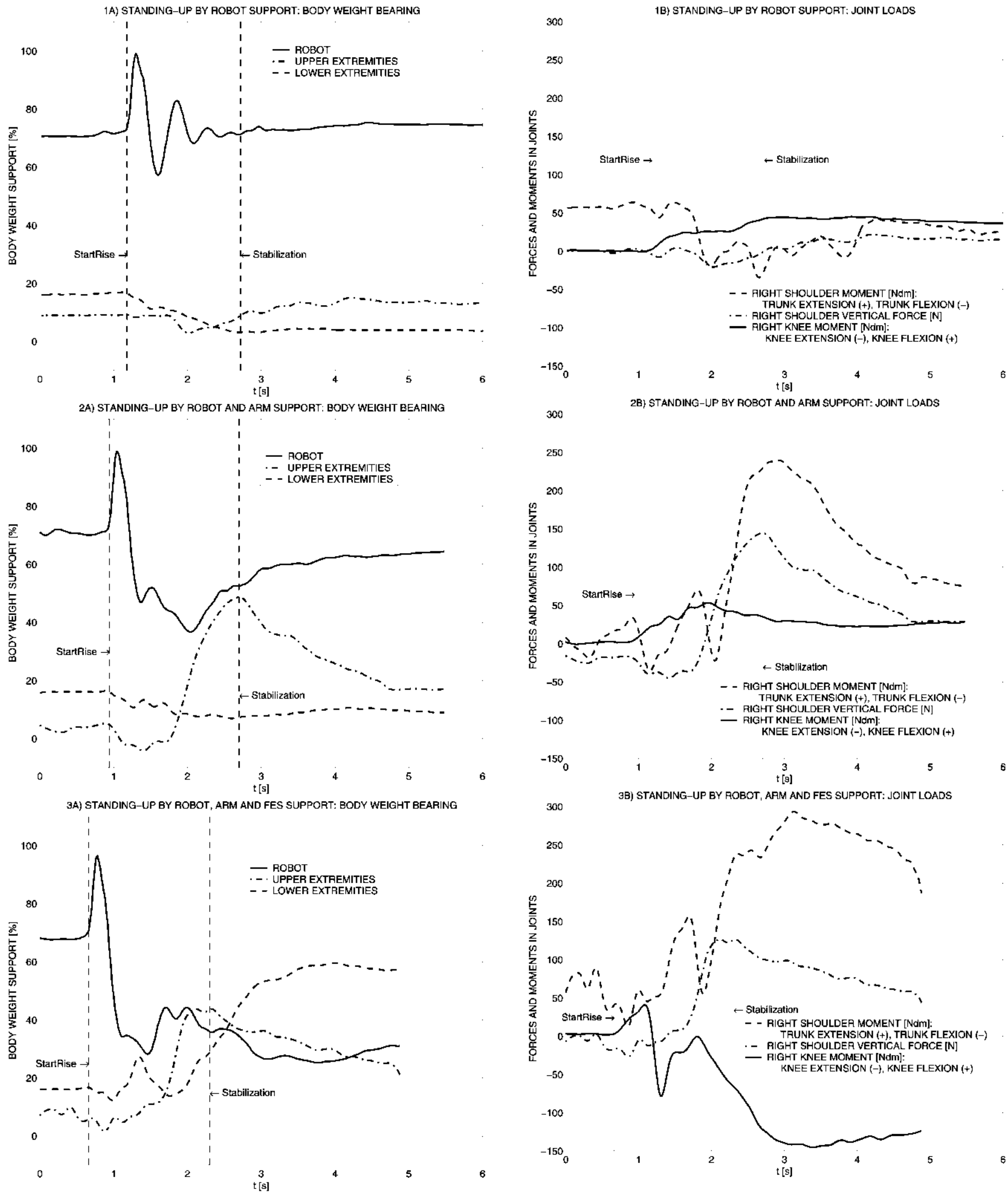

Figure 4. Bodyweight bearing and joint loads during: (1) robot-assisted. standing up, (2) robot- and arm-assisted standing up, and (3) robot-arm and FES-assisted standing up.

Graphs 3A and 3B of figure 4 present an example of standing up with the help of simultaneous contributions from the robot device, arm support, and FES of the paralysed lower limbs. Here again, the robot device contributed significantly at the beginning of the rising process. Afterwards, the support of the arms and the electrically stimulated lower limbs increased, attaining 45% and 20% of the bodyweight bearing respectively at the beginning of the stabilization phase. The artificially invoked knee joint moment reached its maximum approximately one second after the knee joint fully extended. As the standing position was approached, the subject released her arms and the robot, while loading the lower extremities with up to 60% of her bodyweight. Interestingly, as well as the higher knee joint moment detected, higher shoulder moment in the sagittal plane was also detected, implying higher demands for ensuring the upright upper body posture.

Conclusions

A novel rehabilitation robot device intended for augmenting human capabilities during the standing-up manoeuvre was desribed. The device is constructed as 3-DOF mechanism with a control system enabling multiple modes of operation. This paper presents the device configuration and the results of preliminary prototype testing during standing up of a paraplegic subject. In the experiments, the device operated in a position control mode imposing the hip joint motion to the subject along a predefined trajectory. The results demonstrate the applicability of the robot device as an assistive device. The robot support enabled standing up in conditions which would normally require substantial help of a physiotherapist. The subject utilizing the robot support was standing up in her usual way, while easily maintaining her postural stability. She did not report discomfort or annoyance during robot-assisted rising. The robot end-point trajectory programming capability allows selection of different STS transfer motion trajectories during training of standing up. Also, the free trajectory programming feature enables training and measurement in isokinetic conditions.

The results presented also demonstrate the applicability of the robot device as an assessment tool. From the measurement data, the supportive contributions of the upper body voluntary controlled joints, the lower body FES-driven joints, and the robot can be assessed and evaluated. Moreover, joint loadings can be determined via inverse dynamic analysis.

From the control point of view, the conventional positional control algorithm cannot fully satisfy the dynamic requirements. Namely, in the robot-assisted standing up task two dynamic systems are interacting. A high peak in the subject/robot interaction force in the beginning of rising implies that the robot device is a master device which imposes the motion to the subject. To minimize the effect, the impedance control approach is a common solution in the rehabilitation robotics [18, 19]. In this regime, the robot dynamic behaviour is programmable and the interaction intensity predictable. However, the subject has no voluntary control over the training process. For this reason, an explicit interaction force control with the reference accounting for the subject's voluntary activity appears to be an adequate control approach for robot-supported standing up.

Acknowledgements

This work was financially supported by the Republic of Slovenia Ministry of Education, Science and Sport.

References

1. Schultz, A. B., Alexander, N. B., and Ashton-Miller, J. A., 1992, Biomechanical analyses of rising from a chair. *Journal of Biomechanics*, **25,** 1383 – 1391.
2. Ellis, M. I., Seedhom, B. B., and Wright, V., 1984, Forces in the knee joint whilst rising from a seated position. *Journal of Biomedical Engineering*, **6,** 113 – 128.
3. Gellman, H., Sie, I., and Waters, R. L., 1998, Late complications of the weight bearing upper extremity in the paraplegic patient. *Clinical Orthopaedics and Related Research*, **233,** 132 – 135.
4. Burdett, R. G., Habasevich, R., Pisciotta, J., and Simon, S. R., 1985, Biomechanical comparison of rising from two types of chairs. *Physical Therapy*, **65,** 1177 – 1183.
5. Munro, B. J., Steele, J. R., Bashford, G. M., Ryan, M., and Britten, N., 1998, A kinematic and kinetic analysis of the sit-to-stand transfer using an ejector chair: implications for elderly rheumatoid arthritic patients. *Journal of Biomechanics*, **31,** 263 – 271.
6. Wretenberg, P., Arborelius, U. P., Weidenhielm, L., and Lindberg, F., 1993, Rising from a chair by a spring-loaded flap seat: a biomechanical analysis. *Scandinavian Journal of Rehabilitation Medicine*, **25,** 153 – 159.
7. Kralj, A., and Bajd, T., 1989, *Functional electrical stimulation: standing and walking after spinal cord injury* (Boca Raton, FL: CRC Press).
8. Bajd, T., Kralj, A., and Turk, R., 1982, Standing-up of a healthy subject and a paraplegic patient. *Journal of Biomechanics*, **15,** 1 – 10.
9. Bahrami, F., Riener, R., Jabedar-Maralani, P., and Schmidt, G., 2000, Biomechanical analysis of sit-to-stand transfer in healthy and paraplegic subjects. *Clinical Biomechanics*, **15,** 123 – 133.
10. Kamnik, R., Bajd, T., and Kralj, A., 1999, Functional electrical stimulation and arm supported sit-to-stand transfer after paraplegia: a study of kinetic parameters. *Artificial Organs*, **23,** 413 – 417.
11. Riener, R., Ferrarin, M., Pavan, E. E., and Frigo, C. A., 2000, Patient-driven control of FES-supported standing up and sitting down: experimental results. *IEEE Transactions on Rehabilitation Eengineering*, **8,** 523 – 529.
12. Donaldson, N., and Yu, C.H., 1996, FES standing: control by handle reactions of leg muscle stimulation (CHRELMS). *IEEE Transaction on Rehabilitation Engineering*, **4,** 280 – 284.
13. Davoodi, R., and Andrews, B. J., 1998, Computer simulation of FES standing up in paraplegia: a self-adaptive fuzzy controller with reinforcement learning. *IEEE Transaction on Rehabilitation Engineering*, **6,** 151 – 161.
14. Schüldt, K., Ekholm, J., Németh, G., Arborelius, U. P., and Harms-Ringdahl, K., 1983, Knee load and muscle activity during exercises in rising. *Scandinavian Journal of Rehabilitation Medicine*, **15**(suppl. 9), 174 – 199.
15. Mattila, J., and Virvalo, T., 2000, Energy-efficient motion control of a hydraulic manipulator. *Proceedings of the 2000 IEEE International Conference on Robotics and Automation (ICRA '2000)*, edited by R. Carlisle, O. Khatib, IEEE, Piscataway, NJ, USA. San Francisco, USA, pp. 3000 – 3006.
16. De Leva, P., 1996, Adjustments to Zatsiorksy-Seluyanov's segment inertia parameters. *Journal of Biomechanics*, **29,** 1223 – 1230.
17. Spong, M. W., and Vidyasagar, M., 1989, Robot dynamics and control (New York, NY: John Wiley & Sons).
18. Hogan, N., 1985, Impedance control: an approach to manipulation: parts I, II, III. *Journal of Dynamic Systems, Measurement and Control*, **107,** 1 – 24.
19. Kamnik, R., Matko, D. and Bajd, T., 1998, Application of model reference adaptive control to industrial robot impedance control. *Journal of Intelligent and Robotic Systems*, **22,** 153 – 163.