Proceedings of the 2005 IEEE
International Conference on Robotics and Automation
Barcelona, Spain, April 2005

Rehabilitation Robot Cell for Multimodal Standing-Up Motion Augmentation*

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Abstract— **The paper presents a robot cell for multimodal standing-up motion augmentation. The robot cell is aimed at augmenting the standing-up capabilities of impaired or paraplegic subjects. The setup incorporates the rehabilitation robot device, functional electrical stimulation system, measurement instrumentation and cognitive feedback system. For controlling the standing-up process a novel approach was developed integrating the voluntary activity of a person in the control scheme of the rehabilitation robot. The simulation results demonstrate the possibility of "patient-driven" robot-assisted standing-up training. Moreover, to extend the system capabilities, the audio cognitive feedback is aimed to guide the subject throughout rising. For the feedback generation a granular synthesis method is utilized displaying high-dimensional, dynamic data. The principle of operation and example sonification in standing-up are presented. In this manner, by integrating the cognitive feedback and "patient-driven" actuation systems, an effective motion augmentation system is proposed in which the motion coordination is under the voluntary control of the user.**

Index Terms— **Rehabilitation robotics, standing-up, voluntary control, audio cognitive feedback, granular synthesis.**

I. Introduction

Rising from a chair is a common, however demanding, activity of daily living. Impaired persons and the elderly often have difficulty when rising to a standing position. To compensate for the lack of lifting forces produced by muscles, a handicapped person usually practices an adapted approach to the standing–up manoeuvre. Normally, the upper extremities take over the body weight lifting role. This requires a fit upper body. Additionally, in patients with lesions of the CNS, the standing–up exercise can be facilitated with the help of functional electrical stimulation (FES) evoking muscle contractions in the paralyzed extremities [1]. In clinical praxis, the knee extensors (quadriceps muscle groups) are stimulated to elicit moments in the knee joints [2], [3].

When training an impaired subject to adapt to a new standing–up approach, the trainee needs to be, in numerous repetitions, restrained in a position trajectory and adequately supported to maintain postural stability. Furthermore, investigating new FES control approaches requires feedback to evaluate the effects of improvements. Training of standing–up is usually performed by the manual support of physiotherapists using also different mechanical aids. The back sled and seesaw construction are typical examples [4], [5]. Mechanical aids are usually constructed as counterweight-based passive devices intended to aid the subject and assure his stability. None of the devices provides feedback information about the rising process or the capability of motion trajectory programming.

For these reasons we have developed the standing–up robot assistive device [6]. The device is designed as a 3 DOF mechanism driven by an electrohydraulic servosystem with a standard bike seat mounted at the end-effector. Sitting at the seat the impaired person is supported under the buttocks. The motion trajectory of the seat is constrained to the subject's sagittal plane. The robot mechanical configuration allows the subject to actively participate in rising. Moreover, to integrate the subject's voluntary activity in the control of robot device, a special control algorithm is proposed [7]. The algorithm allows to the subject to voluntarily control the robot support by his own activity.

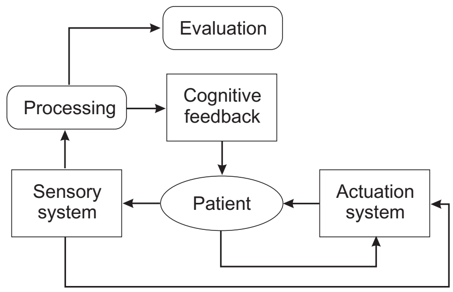

Fig. 1. Multimodal standing-up motion augmentation

In this paper, we are proposing the integration of the standing-up robot device with the FES, measurement and cognitive feedback systems. The objective of the integration is to build a robot cell for multimodal standing-up motion augmentation. The concept is presented in Figure 1. In the robot cell, the subject is supposed to be assisted by the actuation system providing the supportive forces. As an actuation, the standing-up robot is used to generate the external support to the human body. In the case of paraplegia, the external support can be additionally combined with FES. FES is used to evoke the internal body forces by employing the subject's paralyzed muscles. In addition to the actuation, the cognitive feedback is employed to inform the subject about the quality of standing-up pattern and anomalies. The sensory system implemented in the robot cell performs assessment of the kinematics and dynamics of

*This work is partially supported by Slovenian research program #P2-0228/2.06 to R. Kamnik and T. Bajd, and EPSRC grant GR/M76379/01CNSF, SFI grants to J. Williamson and R. Murray-Smith

standing-up maneuver. The data acquired are processed and fed to the cognitive and actuation systems or used for the off-line evaluation. The innovative segment of the proposed robot cell is that it provides the training regime which is under the voluntary control of the subject. Utilizing the robot cell, the subject is in position to exercise the standing-up in a preferable manner and speed and to adapt his motion pattern with regards to the cognitive feedback information.

The paper is organized as follows. In the second section, the mechanical design of the standing-up robot device and its control system are described. The third section presents the robot cell configuration. The control approach proposed for the patient-driven robot-supported standing-up training is described in the fourth section, while the fifth section outlines the approach to cognitive audio feedback synthesis. In the conclusions, the advancements of the proposed technology are discussed.

II. STANDING–UP ROBOT ASSISTIVE DEVICE

In the standing–up manoeuvre, the upper body can be considered as restricted to three degrees of freedom of motion. It moves vertically and horizontally in the sagittal plane, while changing its orientation in the antero-posterior direction. Thus, it can be reasonably assumed that the majority of subjects who are unable to stand-up (elderly, people with paraplegia or even some tetraplegic patients) will be able to control their upper body orientation by means of 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-assisted standing–up. The novel robot device, developed according to the above criteria, is presented in Figure 2. The robot assistive device is a 3 DOF

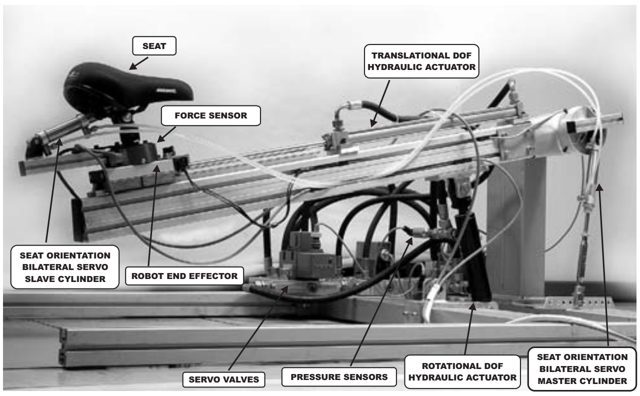

Fig. 2. Standing–up robot assistive device

mechanism which, in its way of supporting the subject, resembles half of a seesaw. The impaired subject sits on a standard bike seat mounted at the robot end-effector. Positioning of the end-effector is accomplished by positioning of two robot segments. The first segment is rotating around its axis on the robot base, while the second translational segment is moving longitudinally along the first segment. 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. The hydraulic bilateral system consists of two cylinders, master and slave, with the master piston coupled to the driving first robot segment. Under the seat mechanism the six axis JR3 force/torque sensor (JR3 Inc., Woodland, USA) is mounted in order to assess the contact force between the robot end-point and the rising subject. In this manner, subject/machine interaction, and hence the robot assistance to the standing-up process, can be assessed and controlled on-line.

The robot mechanism is driven by the electrohydraulic servosystem. The system is powered by a hydraulic pump providing a pressure of 50 *bars* and hydraulic current of 1 l/s. The pump performance allows a maximal speed of the robot end-effector up to 2 m/s. The Moog servovalves (Moog Inc., New York, USA) are used to control the pressure difference applied to the linear hydraulic cylinders driving the rotating and translating link. In this way, two operational modes are provided. 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, explicit control of interaction force is possible.

III. CONFIGURATION OF THE ROBOT CELL FOR STANDING-UP MOTION AUGMENTATION

In Figure 3 the configuration of proposed robot cell for standing-up motion augmentation is illustrated. The cell incorporates the standing-up robot device, the audio feedback system and the measurement instrumentation. Human body symmetry during standing-up task is presumed. Hence, measurements are accomplished only for the patient's right side. The robot, foot and arm reactions are assessed by multidimensional force sensors. The force plate mounted in the floor acquires the foot supportive forces. The arm supportive forces are assessed by the robot force wrist implemented in the arm supportive frame, while the robot support is measured by the similar sensor mounted under the seat. The assessment of motion kinematics is performed by an optical system or combination of simpler sensors. For example, lower extremity joint angles can be estimated from information about the robot end point and foot positions, while HAT acceleration and angular velocity can be acquired using accelerometers and a gyroscope attached to the trunk.

The operation of sensory, actuation and feedback systems is controlled by a computer system built on a 1 GHz PC Pentium III platform. On the platform, the RTLinux real time operating system is running at a constant sampling rate of 2 KHz. Two PCI interface boards are employed to acquire analog and encoder signals. Via another PCI D/A converter board the hydraulic servosystem is controlled. Besides, a computer sound card and a laudspeaker are used to generate the audio feedback signal.

The incorporation of FES actuation system is optional for paraplegic subjects. The surface stimulation of the M.quadriceps muscle group is common in praxis. The knee extensors can be stimulated with intensity level that

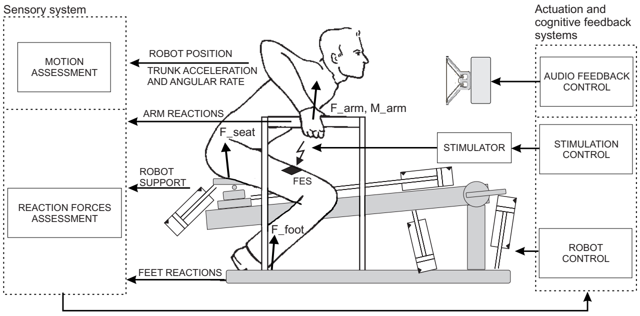

Fig. 3. Configuration of the robot cell for standing-up motion augmentation

corresponds to the desired knee joint torque profile or according to the phase of the rising process. The stimulator is built as a galvanically separated unit and it is controlled via a serial communication port.

IV. HUMAN VOLUNTARY ACTIVITY INTEGRATION IN THE CONTROL OF A STANDING-UP ROBOT - PDRAMA APPROACH

As an alternative to position or impedance control [8], [9], we have developed a control approach integrating human voluntary activity into the robot control scheme. In the approach, the robot is supposed to operate in a force control mode, while the force reference is determined according to the rising subject's activity. In this way, the artificial robot controller is integrated into the control actions of the intact neuromuscular system of the subject. Similar to approaches proposed in [5] and [10], the hand and foot support forces are used to characterize the subject's volition and are thus used as feedback to the controller. We named the approach "Patient-Driven Robot-Assisted Motion Augmentation" (PDRAMA).

The basic idea behind the calculation of the reference force is to quantify the deficit in the force and moment equilibrium of the trunk. Namely, if we simplify the situation and consider the subject's head, arms and trunk (HAT segment) as a rigid body, the balance equations for the forces and moments acting on this body segment can be defined. During motion, the HAT segment is supported by the lower and upper extremities in the hip and shoulder joints. The contributions of shoulder joint force ($\underline{F}_{sh}$), shoulder joint moment ($\underline{M}_{sh}$), hip joint force ($\underline{F}_{hip}$), hip joint moment ($\underline{M}_{hip}$) and the inertial contributions due to translational and angular accelerations are illustrated in Figure 4. Assuming human body symmetry during rising, the HAT motion can be considered as planar, constrained to the subject's sagittal plane. If the joint reactions and the HAT motion are known, the HAT balance can be determined and thus postural stability assured by applying additional external force to the HAT segment. Additional force ($\underline{F}_{robo}$) is, in robot assisted standing-up, contributed by the robot device supporting the HAT segment near the hip joints. Following the Newton-Euler approach to analyzing rigid body motion dynamics, the force and moment

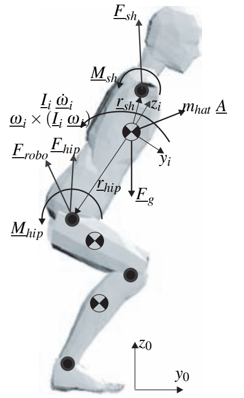

Fig. 4. Forces and moments in robot-assisted standing-up acting to the HAT segment

balance equations for the HAT segment can be defined as:

$$\underline{F}_{hip} + \underline{F}_{sh} + \underline{F}_{g} + \underline{F}_{robo} = m\ \underline{A} \qquad (1)$$

$$\underline{M}_{hip} + \underline{M}_{sh} + \underline{F}_{hip} \times \underline{r}_{hip} + + \underline{F}_{sh} \times \underline{r}_{sh} + \underline{F}_{robo} \times \underline{r}_{hip} = d(\underline{I}_0\ \underline{\omega}_0)/dt \qquad (2)$$

In (1) and (2) the notation of forces and moments corresponds to notation in Figure 4, while the vectors $\underline{r}_{hip}$ and $\underline{r}_{sh}$ describe the position of the hip and shoulder joints with respect to the HAT center of mass. $\underline{F}_g$ stands for gravitational force. The parameters m_{hat}, $\underline{I}_0$ and $\underline{\omega}_0$ denote the HAT segment mass, inertia and angular velocity, respectively. All three parameters are expressed with respect to the inertial coordinate system. Normally, it is more convenient to describe the moment balance with respect to the local coordinate system of the HAT segment. The resulting equation is then:

$$\underline{R}_0^{iT}\ \underline{M}_{hip} + \underline{R}_0^{iT}\ \underline{M}_{sh} - (\underline{R}_0^{iT}\ \underline{F}_{hip}) \times \underline{r}_{i,hip} - (\underline{R}_0^{iT}\ \underline{F}_{sh}) \times \underline{r}_{i,sh} - -(\underline{R}_0^{iT}\ \underline{F}_{robo}) \times \underline{r}_{i,hip} = \underline{I}_i\ \dot{\underline{\omega}}_i + \underline{\omega}_i \times (\underline{I}_i\ \underline{\omega}_i) \qquad (3)$$

In (3), the inertial tensor $\underline{I}_i$ and the vectors $\underline{r}_{i,hip}$, $\underline{r}_{i,sh}$ represent parameters expressed in the HAT coordinate system and are thus constant. The relation between the inertial and the local coordinate system is described by the homogenous rotational matrix $\underline{R}_0^i$.

To assure postural stability, equations (1) - (3) must be satisfied in each time instant. Formulating vector equations along horizontal and vertical directions, and expressing the components of the robot support, we get the algorithm for determining the desired robot supportive force. All variables and parameters must be known, and the equations must be decoupled. Parameters of the body segments (masses, center-of-mass positions) can be estimated using anthropometric data [11], while the shoulder and hip forces and moments need to be assessed via the inverse dynamic approach utilizing the force reactions and kinematic measurements.

A. Extended Kalman Filter algorithm

For decoupling (1) and (3), an Extended Kalman Filter (EKF) algorithm was employed. Kalman filtering is a common approach in multisignal integration tasks relying on an approximate analytical model of the system [12]. In the EKF, the model is represented by a nonlinear state space description incorporating state and measurement difference equations:

$$\underline{x}_{k+1} = \underline{f}(\underline{x}_k, \underline{u}_k, \underline{w}_k) \quad (4)$$

$$\underline{z}_k = \underline{h}(\underline{x}_k, \underline{v}_k) \quad (5)$$

In (4) the nonlinear function $\underline{f}$ relates the state vector $\underline{x}$ and the input vector $\underline{u}$ at time step k to the state at step $k+1$. The measurement vector $\underline{h}$ in (5) relates the state to the measurements $\underline{z}_k$. Vectors $\underline{w}_k$ and $\underline{v}_k$ denote the superimposed process and measurement noise, respectively.

We defined the state vector as $\underline{x}_k = [\phi\ \dot{\phi}\ \ddot{\phi}\ A_y\ A_z\ f_{y,robo}\ f_{z,robo}]^T$, where ϕ stands for the trunk inclination angle, A_y and A_z for the vertical and horizontal accelerations, and $f_{y,robo}$ and $f_{z,robo}$ for the trunk vertical and horizontal robot supportive force. The particular functions of the state equation were derived from (1) and (3).

Measurement vector $\underline{z}_k = [\dot{\phi}\ a_y\ a_z\ f_{y,sh}\ f_{z,sh}\ f_{y,hip}\ f_{z,hip}\ m_{x,sh}\ m_{x,hip}]^T$ incorporates all the measurement values. Trunk inclination rate $\dot{\phi}$ and accelerations a_y, a_z are supposed to be measured by a gyroscope and accelerometers attached to the trunk. The shoulder and hip reactions $(f_{y,sh}, f_{z,sh}, f_{y,hip}, f_{z,hip}, m_{x,sh}, m_{x,hip})$ are assessable by an inverse dynamics calculation for the lower and upper extremities. The particular functions of the nonlinear measurement equation were expressed from (1) and (3) also.

The discrete-time EKF algorithm is implemented as in [13]. The complete set of equations is shown below. The EKF measurement update equations are:

$$K_k = P_k^- H_k^T (H_k P_k^- H_k^T + R_k)^{-1}, \quad (6)$$

$$\hat{\underline{x}}_k = \hat{\underline{x}}_k^- + K(\underline{z}_k - \underline{h}(\hat{\underline{x}}_k^-, 0)), \quad (7)$$

$$P_k = (I - K_k H_k) P_k^- \quad (8)$$

while the EKF time update equations are as follows:

$$P_{k+1}^- = A_k P_k A_k^T + Q_k \quad (9)$$

$$\hat{\underline{x}}_{k+1}^- = \underline{f}(\hat{\underline{x}}_k, \underline{u}_k, 0) \quad (10)$$

The EKF propagates the state and error covariance estimates (10) and (9) by computing the filter gain matrix K_k (6), and by updating the state and covariance estimates based on the measurement residual (7) and (8). Matrices A_k and H_k are the Jacobian matrices of partial derivatives of $\underline{f}()$ and $\underline{h}()$ with respect to vector $\underline{x}_k$. Matrices Q_k and R_k represent the process and measurement noise covariances.

B. Evaluation of the PDRAMA control approach

The PDRAMA control approach proposal was evaluated by a simulation study. For this purpose, the standing-up manoeuvre of a paraplegic subject was modelled in a simulation environment. In the simulation model, the models of voluntary activity, robot support and dynamics of human body motion were incorporated. The simulation results were compared with the measurement data acquired in the actual robot-supported standing-up trials of a paraplegic subject. In the experiments, a person with paraplegia was involved (subject MT, female, 30 years, 171 cm, 75 kg, injury level T 4-5). In the experimental trials the robot device was operating in the position control mode. No interaction control was involved in this regime. In the experiments, the robot accomplished motion along the reference trajectory while the subject was trying to adapt to the imposed pelvis position. In Figure 5 the experimental setup is shown incorporating the robot assistive device, the arm supportive frame and the measurement instrumentation.

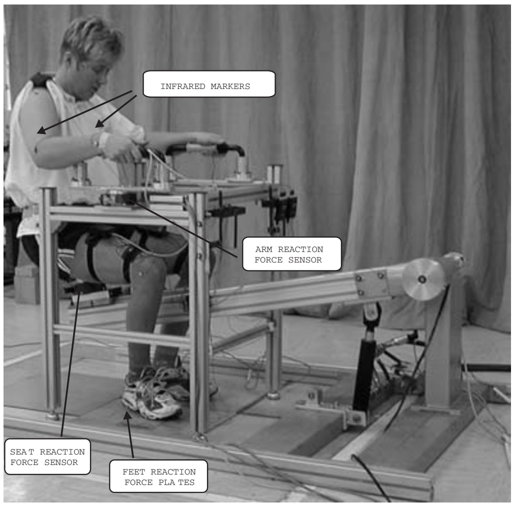

Fig. 5. Paraplegic subject in the experimental setup

In the simulation model, the motion of the human body in the standing–up process was simulated in the Matlab–Simulink software environment. The dynamics model of the human body included three rigid body segments - shanks, thighs and HAT - constrained to sagittal plane motion. In the model, the human body anthropometric parameters [11], the visco–elastic properties of the joints [14] and the human voluntary control were incorporated. As with paraplegic subjects, no active moments were applied in the lower extremities. Human volition was modelled via three PD controllers that generated the shoulder forces and moment, regarding the difference between the current and the desired trunk position and orientation. The desired trajectory had been assessed in the actual standing-up of a paraplegic patient. In each integration step of the simulation track, the robot supportive force was determined by the Kalman filter algorithm and applied as an external force vector at the hip joint mimicking the robot support.

In the evaluation results, two approaches to the robot control are compared. The actual standing-up facilitated by the position controlled robot device is compared to the simulated standing-up. In simulated standing-up, the model of the subject is supported by the force determined by the PDRAMA algorithm.

In Figure 6 the contributions to the body weight support are shown for two examples of the robot-assisted standing–up. The upper graph presents the vertical component of the shoulder joint force. Below the graph, the body motion kinematics is presented by dark and white stick figures illustrating the simulated and actual standing-up examples. The arrows describe the amplitude and direction of the force acting in the shoulder joint. The line style of the arrows corresponds to the line style in the graph. The lower graph represents the vertical robot interaction force acting near hip joints. In this way, Figure 6 represents the voluntary activity of the subject and his robot assistance during rising.

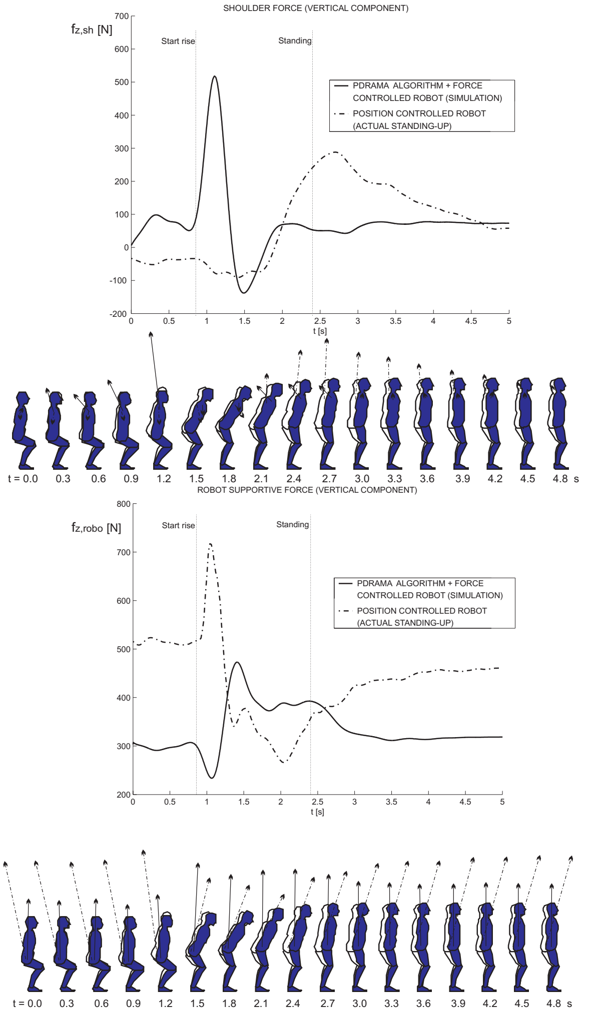

Fig. 6. Voluntary activity and robot support in robot-assisted standing-up: measured results (robot in position control mode) and simulation results (robot in force control mode, supportive force determined by the PDRAMA algorithm)

The evaluation results demonstrate that a similar motion pattern is demonstrated in actual and simulated standing-up examples. However, from Figure 6 a fundamental difference between the control approaches can be observed. In actual standing-up facilitated by the position-controlled robot device, a high peak in the subject/robot interaction force is noticed at the beginning of rising. The high interaction implies that the robot device acts as a master device which imposes the motion to the subject. As a consequence, the low voluntary activity of the subject is present in body weight lifting. On the other side, in the PDRAMA simulation example, it is evident that the subject initiated and guided the motion by upper body activity. The robot provided needed support only. In this way, voluntary control over the motion manoeuvre is assured to the subject. Moreover, since the measured reaction forces can be scaled before being fed to the controller, the amount of the body weight support between the voluntary and the robot contributions can be varied. This feature opens the possibility for altering the training conditions in robot-assisted standing–up.

V. GRANULAR SYNTHESIS FOR COGNITIVE AUDIO FEEDBACK IN STANDING-UP

A simple model for enhancing user performance with training system is to augment the users's proprioception with audio. This involves sonifiying the aspects of the motion maneuver state space corresponding to physical motion; e.g. position, velocity or acceleration. This can help the user intuitively understand how movements he is making are perceived by the system and potentially accommodate the movement in the relevant dimension.

Here we describe a general framework for producing formative audio feedback based on granular synthesis [15], [16]. Granular synthesis is a probabilistic sound generation method, based on drawing short (10-500 ms) packets of sound, called "grains" or "granules", from source waveforms. A large number of such packets are continuously drawn from various sources, shaped so as to avoid discontinuities and summed. Figure 7 shows the basic process.

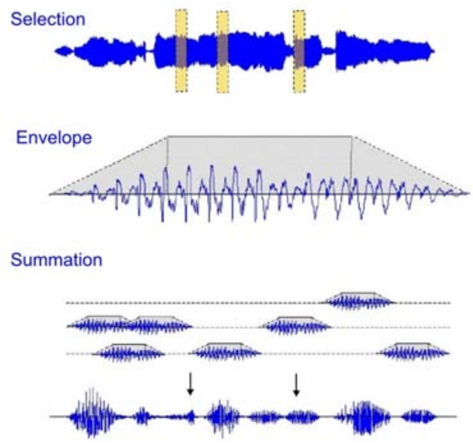

Fig. 7. Simple granular synthesis process. A much greater number of grains would be used in practice for a smoother waveform. When a new grain is created, a section of the source waveform is copied, the position of which being determined by the distribution over waveform time. This section is then enveloped. All of the currently active grains are summed to produce the final output.

Even in situations where other synthesis techniques could be used, granular synthesis gives strong, pleasing textures which are easily manipulated in an elegant and intuitive manner. It also has the advantage that a distribution can be defined over time inside the source waveform, defining the probability of a grain being drawn from a specific time index in the wave. This allows for effective probabilistic time-stretching, which is a powerful tool in interactions where progress towards some goal is of importance, as it is in standing up.

A verbal description of the desired standing-up behaviour might be an informal specification such as *"At the beginning of standing-up, the position of COM is the most important, especially horizontal component* COM_y*. The position* COM_y *is related to the trunk inclination, thus* ϕ_{trunk} *is important too. During the standing-up it is important for the subject to turn the motion from the horizontal to the vertical. For successful redirection the tracking of COM velocity is important, especially tracking the change in velocity direction. At the end of rising, again*

COM_y and vertical trunk inclination demonstrate that the maneuver is over." This sort of suggestion needs to be converted into an audio display which the subject can use to guide their behaviour. Desired positions of variables such as the initial and final positions of *COM* are relatively easy to specify, via probability distributions around the reference values. Turning points such as the change in *COM* velocity are landmarks which need to be highlighted to the user. Predictive techniques which can emphasize expected deviation from the reference trajectory in time for the user to take corrective action can be used to 'quicken' the audio display. Another simple but effective training technique to reduce jerky motions is to link a splashing noise to events in the higher (e.g. 3rd) derivatives of the position signal, explaining to the subject that they should 'avoid making ripples while moving'. This is feedback which makes them aware of the jerk, and can help them smooth their motions in future attempts.

An example audio output in standing-up trial generated with granular synthesis is presented for demonstration purposes. The state vector was described as $x(t) = [\phi_{trunk}\ \dot{\phi}_{trunk}\ COM_y\ COM_z\ \dot{COM}_y\ \dot{COM}_z]$ encompassing trunk inclination angle and angular velocity, and trunk center-of-mass (COM) position and velocity. The desired trajectories were acquired in real standing-up, while the actual in simulated track. For clarity, in Figure 8, we present a caricature of the simplest sonification case. Here the error in the subject's state, compared to the reference signals is converted to an audio signal.

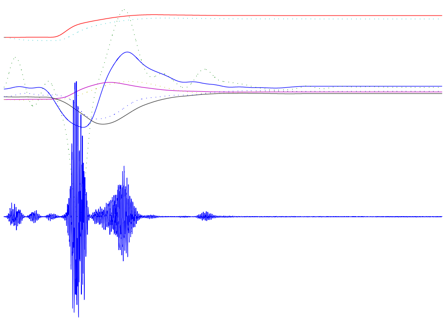

Fig. 8. Schematic example mapping standing (dotted lines) compared with reference (solid) to audio output (lowest plot).

VI. CONCLUSIONS

This paper proposes a rehabilitation robot cell intended for augmenting the human capabilities in the standing-up manoeuvre. The robot cell is based on the rehabilitation robot device, FES system, measurement instrumentation and cognitive feedback system. It enables the multimodal training regime that encourages users for their own activity. For the robot control, the PDRAMA algorithm is presented which incorporates human voluntary activity into the robot control scheme. The algorithm determines the interaction force between the subject and the robot, thus generating the reference to the robot explicit force controller. The algorithm controls the robot motion without the need for specific reference defined. It accounts for the contributions from trunk inertia in dynamic motion and the contributions from the lower and upper extremities to body weight lifting forces. In this way, a unique approach in rehabilitation robotics has been developed: a "patient-driven" control of robot-assisted training. Moreover, with altering of body weight bearing portions between the robot and the subject the standing-up training regime can be varied, depending on the subject's etiology and progress.

The multimodality of the robot cell is enhanced by the cognitive feedback system. Providing the continuous feedback during voluntary controlled motion allows the subject to respond to the system in real-time and in this way accommodate the motion pattern. Audio is used to present high-dimensional, dynamic data in a continuous feedback. For these purposes, the granular synthesis is employed. A simple example of feedback synthesis in standing-up is demonstrated.

The robot cell described presents an efficient tool for standing-up training and evaluation. The remaining issues in the development are the implementation of the proposed algorithms to the robot cell controller and the evaluation of the therapeutic benefits of robot supported standing-up training.

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