Department of Veterans Affairs

Journal of Rehabilitation Research and Development Vol. 37 No. 6, November/December 2000
Pages 681–691

A multi-purpose rehabilitation frame: A novel apparatus for balance training during standing of neurologically impaired individuals

Zlatko Matjačić, PhD; Inger Lauge Johannesen, MD; Thomas Sinkjaer, PhD
Center for Sensory-Motor Interaction, Aalborg University, Aalborg, Denmark; Spinal Unit, Viborg Hospital, Viborg, Denmark

Abstract—We present a novel mechanical apparatus, named Multi-purpose Rehabilitation Frame (MRF), and methods for balance training during standing of neurologically impaired individuals. The device has two degrees of freedom (DOF), which allow for constrained movement of both lower limbs and pelvis in the sagittal and frontal planes. The MRF aims at improving balancing in impaired individuals by providing a stiffness support and action of perturbations, which facilitate development of alternative balancing strategies. The level of stiffness support and strength of perturbations, which are generated by means of two hydraulic servo-controlled actuators, can be selected according to current balancing abilities of an impaired individual. We further present preliminary results of nine days of balance training in two paraplegic and two incomplete tetraplegic subjects standing in the MRF. All subjects improved their balancing abilities as measured from the level of needed supporting stiffness provided by the MRF.

Key words: *balance, neurological impairment, neurological rehabilitation, standing, therapy.*

This material is based upon work supported by the Danish National Research Foundation, Holbergsgade 14,1. DK-1057 Kobenhavn K, Denmark. Also, the first author was partially supported by the Institut Jožef Stefan, Jamova 39, 1000, Ljubljana, Slovenia.

Address all correspondence and requests for reprints to: Zlatko Matjačić, PhD, Assistant Professor, Center for Sensory-Motor Interaction, Aalborg University, Frederik Bajers Vej 7, D 3, DK-9220 Aalborg, Denmark; email: zm@smi.auc.dk.

INTRODUCTION

Every year approximately two million people in Europe and the United States become severely affected in their ability to maintain balance while standing. The most frequent causes of neurological impairment are stroke, traumatic brain injuries, and spinal cord injuries (SCI) (1). Impaired individuals can be divided into two groups according to their residual balancing abilities. The first group is comprised of subjects with a diminished ability to maintain balance (e.g., hemiparesis, paraparesis, and tetraparesis), while the second group is characterized by severe impairment (hemiplegia) or complete loss of balancing abilities (paraplegia and tetraplegia).

The goal of neurological rehabilitation for the group of individuals with diminished balancing abilities is to retrain the residual peripheral and central nervous systems in order to develop alternative movement strategies needed to coordinate motor behavior as efficiently as possible within the constraints imposed by the injury (2). Different methods facilitating the balance relearning process have been developed. The common techniques include the use of oscillatory platform movements while the impaired individual is standing on the platform (3) and use of biofeedback on weight distribution (4,5). Both methods aim to improve balancing abilities in impaired individuals. However, these methods should be applied with caution, as the subjects are exposed to situations of destabilization. There is an inherent problem of protecting the subject from falling, which must be solved to ensure safety. Unfortunately, safety implementations in turn pose a significant limitation to the outcome of a training process (6).

Such methods cannot be applied to the group of severely impaired individuals because they are unable to stand without assistance. Consequently, they are confined to a sitting position, which can result in various medical complications requiring prolonged and expensive professional medical treatment (7). A common therapeutical method for the second group involves passive standing in rigid standing frames or tilt tables. These therapies are rather static and hence an unattractive activity because they do not require a sufficient degree of cognitive involvement.

Thus, there exists a need for new devices and methods that can overcome the limitations of present techniques. New devices and methods should enlarge the scope of task-specific repetitive training (8) and make therapeutic standing more dynamic and attractive. The former is important to people with diminished balancing abilities while the latter is of importance to all impaired individuals.

In this paper we describe a mechanical apparatus named the Multi-purpose Rehabilitation Frame (MRF) and methods for therapeutic standing and balance training using this device. These methods aim to fulfill the needs of both groups of impaired individuals. The MRF device is based on the mechanical rotating frame apparatus (9), which was originally developed to investigate the feasibility of arm-free standing by subjects with complete paraplegia (10). The original apparatus was constrained to one degree of freedom (DOF) and only allowed movement in the sagittal plane, while the MRF has two DOFs and allows movement in the sagittal and frontal planes. Furthermore, we present the results of an experimental investigation conducted with four subjects representing both groups of the impaired population.

MULTI-PURPOSE REHABILITATION FRAME

The Mechanical Apparatus

Figure 1 shows a schematic drawing of the MRF and a person standing in the device. The apparatus consists of a rigid base plate, two 2-DOF rotational joints at the level of subject's ankles, two 1-DOF rotational joints at the level of subject's hips, two vertical supportive rods of adjustable height, an adjustable bracing system, and two servo-hydraulic actuators. Both 2-DOF joints are mounted onto the base plate. Each 2-DOF joint is linked to a 1-DOF joint by a vertical supportive rod. Both 1-DOF joints are connected together by a rigid bracing frame. The subject stands on the base plate wearing plastic long leg braces, which lock the knees while the subject's pelvis is symmetrically braced by the rigid bracing frame. The four aluminum bars that constitute the bracing frame are coated with soft foam. The subject is placed within the MRF in such a way that the legs are positioned parallel to the vertical supportive rods. The axes of rotation in the ankles and 2-DOF joints are co-linear in the sagittal plane and parallel in the frontal plane, thus enabling the same amount of rotation in both planes (shown in **Figure 1**). The axes of rotation of the hips and the 1-DOF joints are parallel in the frontal plane, thus enabling the same amount of rotation in the frontal plane (shown in **Figure 1**). In the sagittal plane the hips are maintained in extended positions by means of a rigid bracing frame that also prevents rotation of the pelvis in the transverse plane. In the described setup the legs and pelvis of the standing person as well as the vertical supportive rods and the bracing system of the apparatus represent a parallelogram structure.

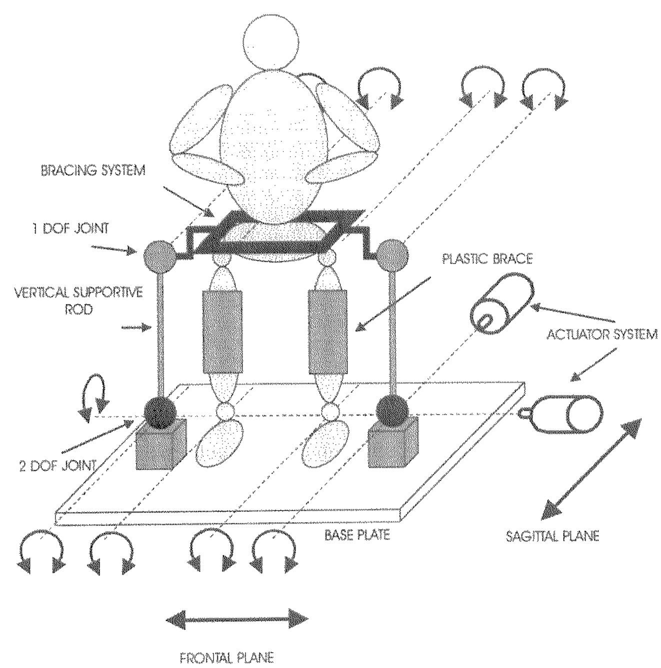

Figure 1.
Schematic of a subject standing in the Multi-purpose Rehabilitation Frame (MRF). The apparatus is composed of base plate, two 2-DOF rotational joints, two 1-DOF rotational joints, and the bracing system, which is put around the pelvis of a standing subject. The apparatus has two DOFs actuated by hydraulic servo systems.

The mechanical apparatus has two DOFs, i.e., one rotation in the frontal plane and the other rotation in the sagittal plane, as shown in **Figure 2**. Both DOFs are actuated by means of hydraulic servo-motors that are located in one of two DOF joints and controlled in real time by a dedicated personal computer (PC). Detailed description on the design of the hydraulic servo systems can be found in (9).

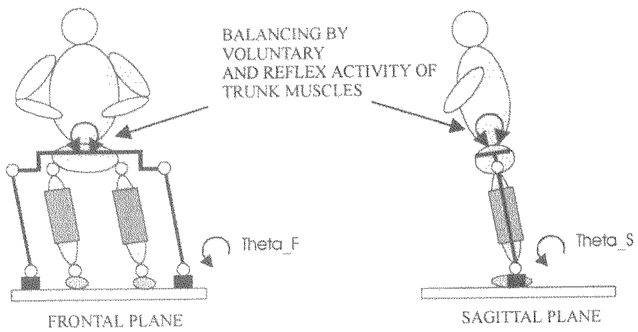

Figure 2.
Schematic of both DOFs of the apparatus. People with paralysis of lower limbs should make use of voluntary and reflex activity of trunk muscles in order to balance. People with partial impairment can balance also by means of lower limb muscular activity. The directions of MRF inclinations in sagittal plane Theta_S and in frontal plane Theta_F are indicated.

Operation of the MRF

The hydraulic servo systems are set up to provide an adequate level of stiffness in both DOFs of the apparatus. In this way the resulting supportive forces at the pelvis of the subject oppose the movement in both planes, very much like passive springs.

People with severely impaired balancing abilities have to use mainly their trunk muscles to maintain balance in the same manner as described in (9,10) and as shown in **Figure 2**. People with diminished balancing abilities should balance also by means of residual lower limb muscular activity. The supporting stiffness for each DOF is selected according to current balancing abilities of a particular subject. The starting level of supporting stiffness for severely impaired individuals should be higher than 10 Nm/degree, as it was shown that this value is sufficient to stabilize the paralyzed lower extremities in a human of average size (10,11). When reducing the level of supporting stiffness, the task of balancing is progressively put more on the impaired individual who needs to make use of residual sensorimotor apparatus in order to maintain posture.

Besides controlling the stiffness, both hydraulic servo systems can induce disturbing torque impulses. The amplitude and duration of a perturbation can be selected according to the abilities of a standing subject. Perturbing torque pulses are delivered randomly in one of eight predetermined directions as shown in **Figure 3**. This feature is provided to facilitate development of alternative balancing strategies by means of task-specific repetitive training of the residual sensorimotor apparatus, mainly in impaired individuals with diminished balancing abilities.

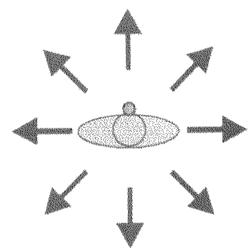

Figure 3.
A top view of the standing subject is drawn, along with the arrows indicating the eight possible perturbation directions.

Safety of Subjects Standing in the MRF

Subjects standing in the MRF wear a full body harness attached by ropes to the safety crane, thus preventing falling. Additionally, the range of motion of the MRF is mechanically limited to ±20 degrees in the sagittal and frontal planes. A person operating the MRF is able to shut down the device by means of an emergency push-button in case of system malfunction. These safety measures not only guarantee safety but also have additional psychological effect such that the impaired individual is not hindered by fear of falling and can fully concentrate on the task of balancing. **Figure 4** shows a neurologically intact individual standing in the MRF.

PRELIMINARY EXPERIMENTAL INVESTIGATION OF THE MRF

Subjects

The data on four male subjects who participated in this preliminary investigation are gathered in **Table 1**. The first two subjects represent the group of impaired individuals with severe impairment of balancing abilities, while the other two subjects represent the group of impaired individuals with diminished balancing abilities.

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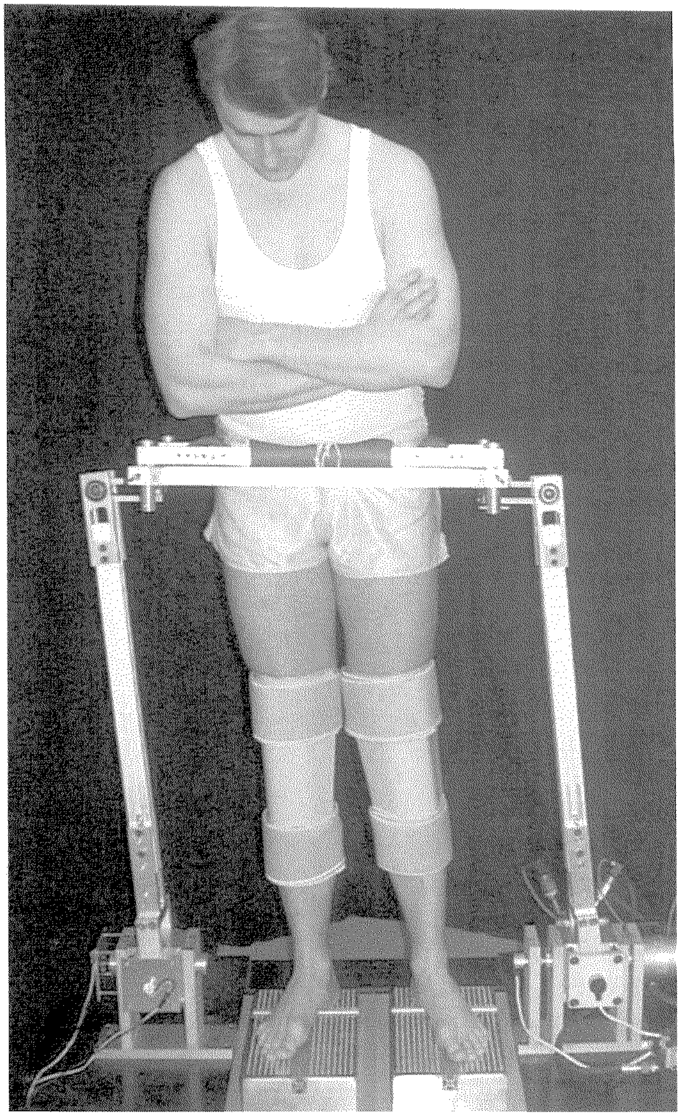

Figure 4.
A photograph of a neurologically intact subject standing in the MRF.

All the experimental activities performed by the subjects were recorded on videotape. The local ethical committee approved the experimental protocol, and the subjects gave consent to participate.

Initial Evaluation of Balance

Subjects were evaluated for balancing abilities prior to initiation of the experimental balancing in the MRF. For Subjects 1 and 2 this was done while they were standing on a standard wooden standing frame. Subjects 3 and 4 were evaluated while standing with support from standard parallel bars. The subjects were asked to release the handles of the standing frame (Subjects 1 and 2) or the parallel bars (Subjects 3 and 4), and balance without support of arms. In this way the task for Subjects 1 and 2 was to balance their trunk while Subjects 3 and 4 needed to maintain balance of the whole body. Their balancing abilities were evaluated by measuring the duration of their arm-free balancing.

Balancing While Standing in the MRF

All subjects underwent 9 days of balancing while standing in the MRF (5 consecutive days followed by 2 days of rest and concluded in another 4 consecutive days of testing). Every day three consecutive standing sessions were performed. The duration of each session was approximately 5 minutes. The pause between 2 sessions was approximately 5 minutes.

First, each subject was placed in standing posture then the bracing frame was placed around the pelvis. During this procedure both DOFs of the MRF were mechanically locked. The subject remained in the standing posture until the last session of a particular day was completed. Before initiating each standing session, we

Table 1.
A description of the subjects who participated in the study.

	Age [yrs]	Height [cm]	Weight [kg]	Lesion	Cause	Time post injury
Subject 1	55	170	76	T-6 complete paraplegia	infection	6 months
Subject 2	51	177	75	T-8 complete paraplegia	infection	7 months
Subject 3	52	189	106	C5-6 incomplete tetraplegia	cervical discus prolapsis	5 months
Subject 4	42	183	70	C5-6 incomplete tetraplegia	cervical discus prolapsis	8 months

varied the stiffness support for each DOF of the MRF in order to determine the level of support within which the subject was comfortable. For the initial value we preferentially chose the level of support at which each subject could comfortably maintain standing on the previous day. However, this was not always an adequate choice, as the overall fitness of the subjects varied from day to day. Thus, the level of stiffness support provided by the MRF during each session was determined by the subject and depended on his judgment of what level of support he anticipated was needed for successful balancing. On some days, due to fatigue, the subjects could not perform all three scheduled sessions.

Subjects 1 and 2 had difficulties maintaining upright posture of the paralyzed lower trunk. Thus, they held onto the front bar of the MRF bracing system throughout the sessions. Subjects 3 and 4 had their arms across the chest and were perturbed throughout all sessions. In the first 3 days, torque pulses were set to an amplitude of 20 Nm and the duration to 100 ms for Subject 3. For subject 4, the amplitude and duration were 10 Nm and 100 ms, respectively. From Day 4 the amplitude of pulses was increased to 50 Nm and 30 Nm for Subject 3 and Subject 4, respectively. The selected intensities were such that Subjects 3 and 4 could recover from them but only if they concentrated on the task.

Throughout the sessions, the inclinations of the MRF (defined in **Figure 2**) were recorded by means of potentiometers mounted in the axes of the MRF. When the subject lost balance (when inclination in either direction of either plane reached 20 degrees), he was gently moved back into upright posture by the experimenter, and the session was continued.

The main variable to show progress in balancing abilities was the amplitude of supporting stiffness provided during the sessions throughout the nine days of balancing while standing in the MRF. Additionally, we qualitatively examined time courses of inclinations in both DOFs of the MRF during the last balancing session performed on each day for Subject 1 and Subject 3.

Evaluation of Balance After MRF Standing

After completion of the experimental MRF standing procedure we repeated the assessment of balancing abilities in all subjects as described above in the subsection on the initial evaluation of balance. In addition, the subjects were asked to pick up an object (a ruler with dimensions of 250 mm × 25 mm × 2 mm, weight approx. 100 g) with one hand from a table in front of them, then to put the object in the other hand, and, finally, to place the object back on the table. The object was put within reach of their arms. Therefore, the subjects needed to compensate for the voluntary arm movements while manipulating the object.

RESULTS

Initial Evaluation of Balance

Subject 1 was not able to maintain trunk posture without arm support. After releasing the frame, he needed to use the arms in order to prevent falling of the trunk within less than 3 seconds. Falling of the trunk occurred equally frequently in all directions, reflecting poor balancing abilities. Similarly, Subject 2 was also unable to maintain trunk posture without arm support.

Subject 3 was able to release his hands from the parallel bars and to maintain balance without arm support in five- to ten-second intervals before having to reach for support to restore balance. Similar performance was seen in Subject 4 except that he could balance without arm support only up to five seconds. The posture of the trunk that Subjects 3 and 4 adopted while standing was a strong forward lean.

Balancing While Standing in the MRF—Subject 1

The results for Subject 1 are shown in **Figures 5** and **6A**. In **Figure 5** the time courses of the inclination angles of the MRF in the sagittal and frontal planes are plotted for the last session performed on each day of the investigation. **Figure 6A** displays the level of stiffness provided by the MRF in the sagittal and frontal planes during each session on each day of the investigation. In the very first session the level of stiffness support was set to 15 Nm/degree for both planes. Such a level of stiffness can support the lower part of the body regardless of the activity of the upper body. The subject was encouraged to use the residual motor abilities of the trunk and arms to move in both planes of motion in order to explore the action of the MRF.

In the third session of Day 1, the level of supporting stiffness was reduced to 12 Nm/degree for both planes. **Figure 5** shows the time course of balancing performance. For the first 100 seconds of balancing it can be observed that the fluctuations of the inclination angle in both planes are very small due to high levels of supporting stiffness. In the remaining 150 seconds of the session we asked the subject to try to put the arms on the chest,

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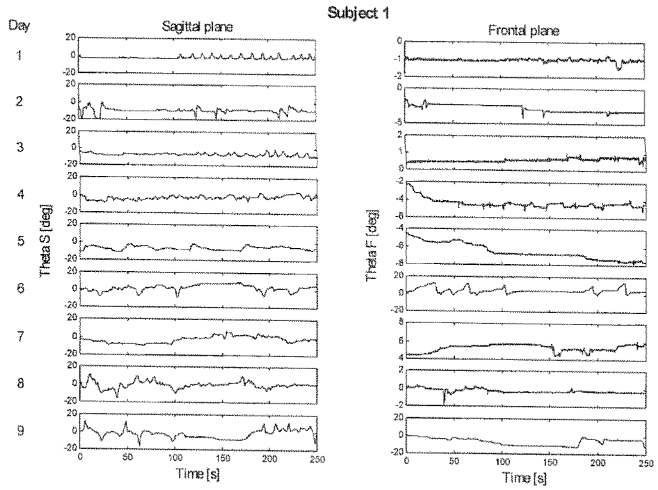

Figure 5.
Time courses of the inclination angles measured in the joints of MRF. The graphs show the performance of Subject 1 in the last session on a particular day for both planes. Positive values indicate inclinations forward in the sagittal plane and to the right in the frontal plane.

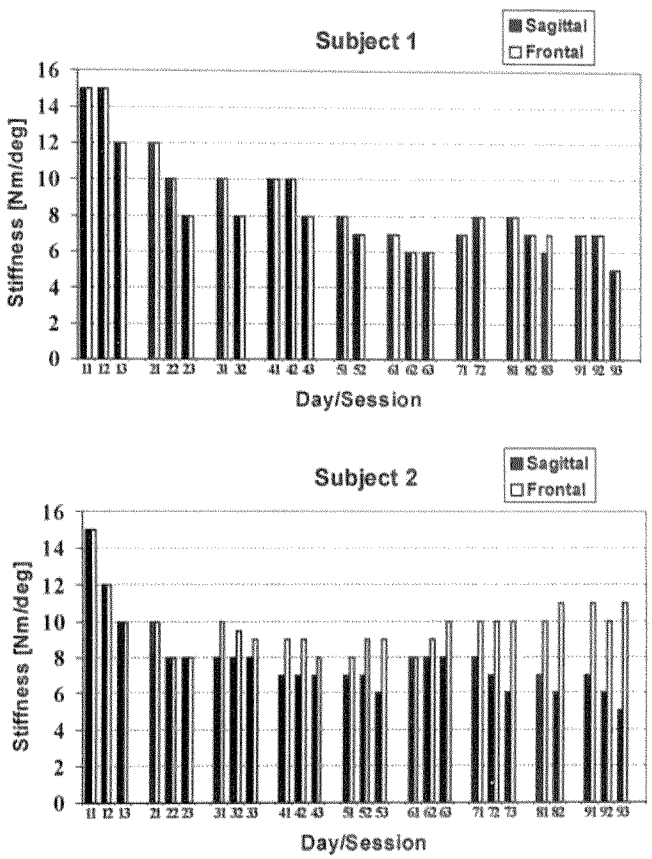

Figure 6.
Supporting stiffness provided by hydraulic servo actuators in the sagittal and frontal planes as set in subsequent sessions throughout the nine experimental days: **A**: Subject 1 and **B**: Subject 2.

which repeatedly resulted in loss of trunk balance, mainly in the sagittal plane (trunk fell forward). When this occurred, the subject prevented the fall by holding onto the bracing system of the MRF.

On Day 2, the level of support was progressively reduced in each consecutive session. From **Figure 5** it can be seen that reduced stiffness support caused the subject to "fall" in the sagittal plane, mainly in the backward direction at the beginning, after approximately the 20th, 120th, 140th, 210th, and 220th seconds of the session. However, the subject remained stable in the frontal plane. This suggests that the stiffness of 8 Nm/degree provided by the MRF was not sufficient to stabilize the body in the sagittal plane but was appropriate for the frontal plane. Active balancing originating from voluntary and reflex activity of the trunk and the arms was needed to maintain the biomechanical structure composed from a standing subject and the MRF in a desired posture. We can see that already on Day 2 the subject learned to balance for limited intervals of time (intervals from the 30th to the 120th second and from the 160th to the 200th second, as displayed in the graph showing the sagittal plane).

From **Figure 6A** we can see that no progress was made in terms of supporting stiffness on Days 3 and 4 as compared to Days 1 and 2. But an improvement in balancing can be seen from **Figure 5**. The subject was able to maintain balance without falling in both planes for the entire duration of a session on Days 3 and 4. For the next four days, **Figure 6A** shows that the supporting stiffness was varied from 6 to 8 Nm/degree in both planes. From **Figure 5** we can see that the subject was able to maintain balance in both planes. However, the fluctuations of the inclination angles in both planes became larger. The reduced level of support put a larger balancing load on the subject, which also resulted in altered posture in the sagittal plane.

Comparison of the posture during Days 1–4 and Days 5–8 reveals that in the earlier phase of the study the subject adopted mainly posture of the lower body inclined backward while in the later course of the study the preferred posture changed toward a more upright stand. On Day 9 the level of support was further decreased to 5 Nm/degree in both planes. From **Figure 5** it appears that the subject was maintaining standing in both planes with considerable difficulty as compared to the previous 4 days.

Balancing While Standing in the MRF—Subject 2

Figure 6B shows the level of supporting stiffness provided by the MRF in the sagittal and frontal planes during each session on each day of the investigation conducted with Subject 2. It can be observed that the pattern of stiffness support in the sagittal plane resembles the one presented for Subject 1 (**Figure 6A**). It can also be seen that the stiffness support in the frontal plane differs from the one for Subject 1. Subject 2 was able to markedly improve balancing in the sagittal plane, while in the frontal plane a stiffness of 10 Nm/degree was needed to enable him to maintain upright posture at the end of the investigation. The time courses of both MRF inclinations in standing of Subject 2 were very similar to the ones observed for Subject 1 (**Figure 5**).

Balancing While Standing in the MRF—Subject 3

The results for Subject 3 are presented in **Figures 7** and **8A** in a similar manner as for Subject 1. In **Figure 7** the time courses of the inclination angles of the MRF in the sagittal and frontal planes are plotted for the last session performed on each day of the investigation. **Figure 8A** shows the level of supporting stiffness, which was set in the first session of Day 1 to 12 Nm/degree. The level of needed support was decreased within the first 3 days of balancing from 12 Nm/degree to only 3 Nm/degree. Note that the stiffness of 3 Nm/degree is needed just to compensate for the weight of the standing frame. Therefore, from Day 3 on, the subject was able to stand and balance arm-free without support of the MRF. The only contribution of the MRF was the perturbing impulses the subject had to cope with. From **Figure 7** we can see that the subject generally was able to maintain balance in both planes simultaneously.

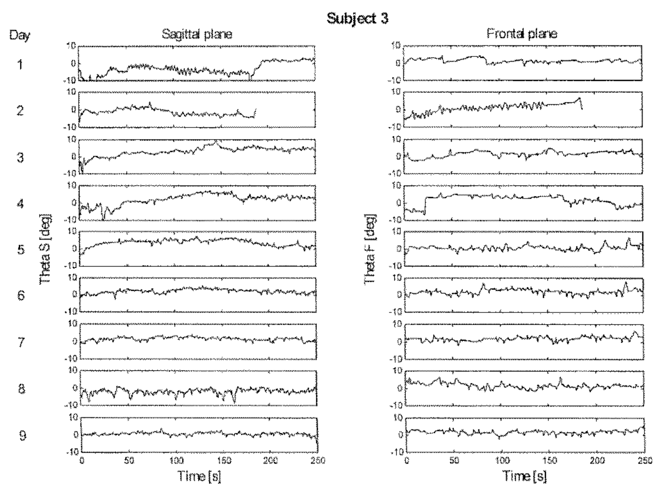

Figure 7.
Time courses of the inclination angles measured in the joints of the MRF. The graphs show the performance of Subject 3 in the last session on a particular day for both planes. Positive values indicate inclinations forward in the sagittal plane and to the right in the frontal plane.

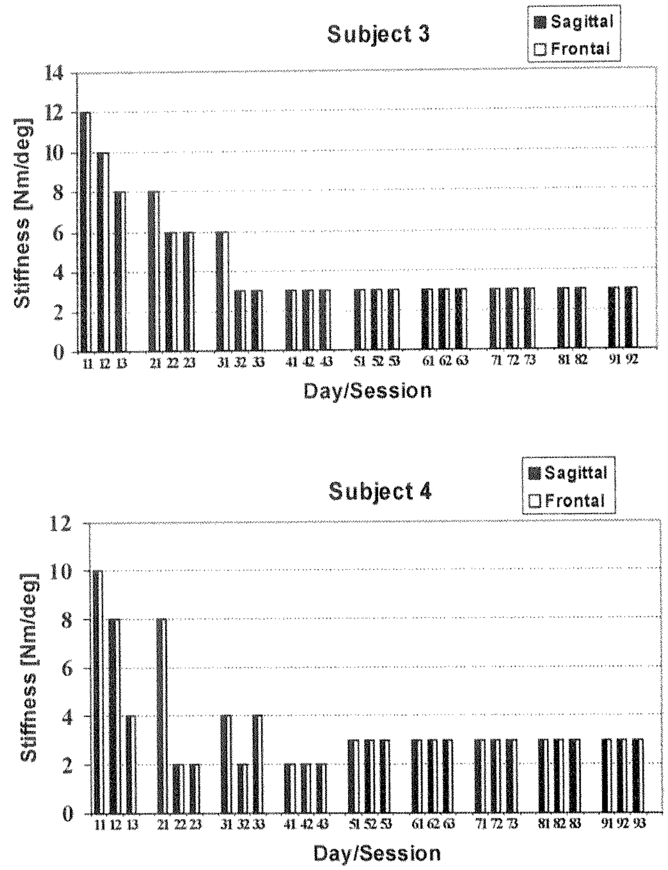

Figure 8.
Supporting stiffness provided by hydraulic servo actuators in the sagittal and frontal planes as set in subsequent sessions throughout the nine experimental days: **A**: Subject 3 and **B**: Subject 4.

A similar observation can be made regarding his posture in the sagittal plane (as for Subject 1). The inclination of the lower part of the body changed from backward inclined (Days 1 and 2) to approximately upright (Days 3 and 4), and finally to a posture in which the lower body was inclined forward while the upper body was held upright. It can also be observed, from **Figure 7**, that the time courses of inclinations in both planes contain a high frequency component, which is not present in **Figure 5** (showing the performance of Subject 1). This is due to the action of the perturbation pulses, which were delivered throughout all the sessions performed by Subject 3.

Figure 9 shows postural responses exercised by Subject 3 on Day 6 after commencement of perturbation in each of eight predetermined directions. In the middle of **Figure 9**, a standing subject is drawn, along with the arrows indicating the eight possible perturbation directions. Each arrow points to two graphs. The first graph shows a phase

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plot of both MRF inclinations while the second graph displays time courses of both MRF inclinations, where the commencement of the perturbation occurred at time 0. The graphs display averaged postural responses, where for each perturbation direction 6 to 8 repetitions typically occurred during each session. It can be seen from **Figure 9** that Subject 3 could recover posture with similar efficiency regardless of the direction of perturbation.

Balancing While Standing in the MRF—Subject 4

Figure 8B shows the level of supporting stiffness provided by the MRF in the sagittal and frontal planes

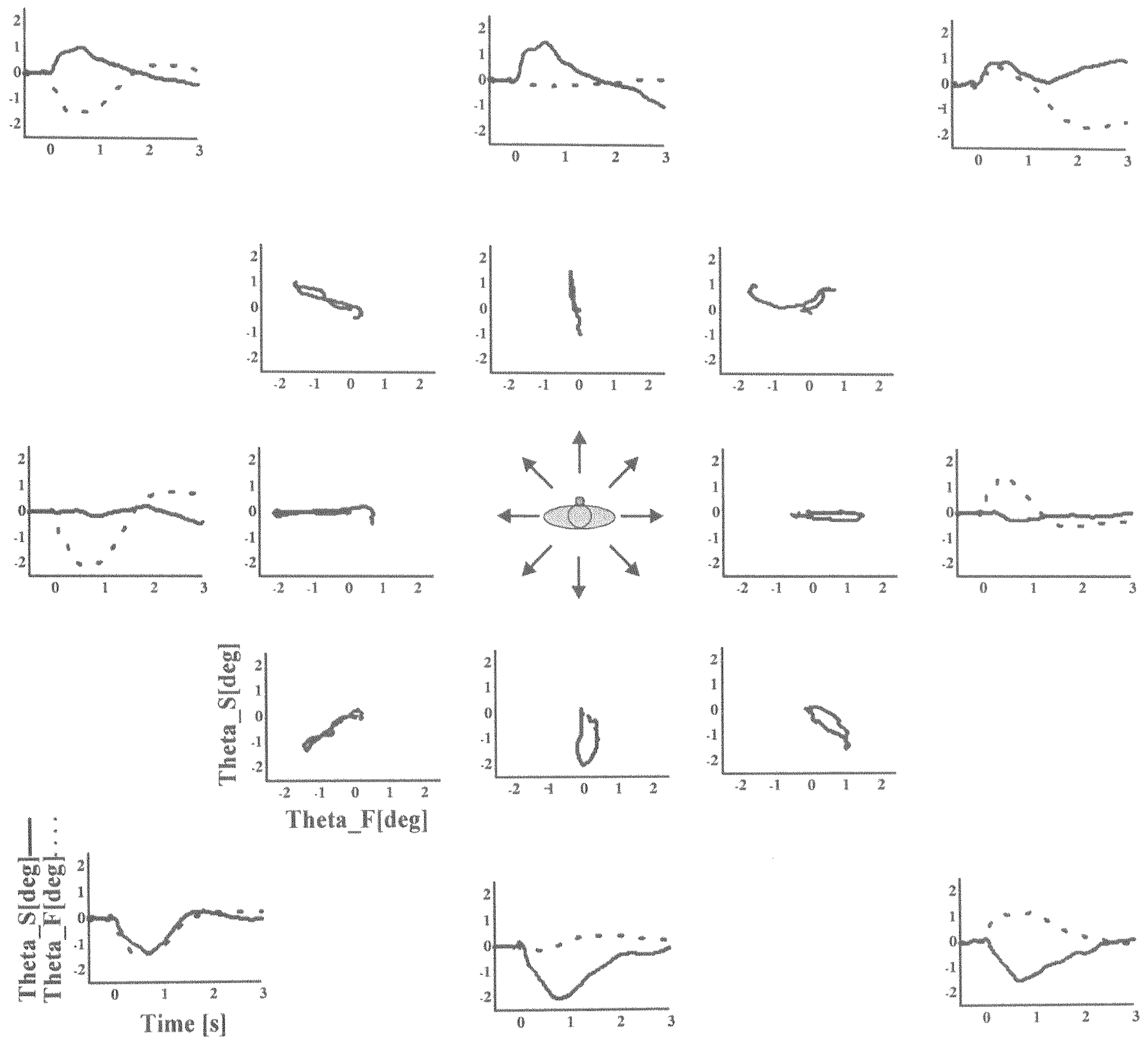

Figure 9.
Postural responses for Subject 3 after commencement of perturbation for all eight directions (Day 6, Session 3). In the middle of the figure a top-view of the standing subject is drawn along with the arrows indicating the eight possible perturbation directions. Each arrow points to two graphs. The first graph (closest to the arrow) shows a phase plot of both MRF inclinations. The second graph displays time courses of both MRF inclinations. The commencement of the perturbation always occurred at time 0. In all eight directions, the mean value of MRF inclinations during half a second prior to the perturbation commencement is subtracted from the same MRF inclinations. All graphs display averaged postural responses, where for each perturbation direction, 6 to 8 repetitions typically occurred during each session.

during each session on each day of the investigation conducted with Subject 4. Almost identical patterns can be observed as in Subject 3. As with Subject 3, Subject 4 needed 3 days of training in the MRF to be able to stand with support of 3 Nm/degree in the remaining days of the investigation. Also, the time courses of both MRF inclinations in standing of Subject 4 were very similar to the ones presented for Subject 3 (**Figure 7**). And similar to the performance of Subject 3, Subject 4 was able to recover after the action of perturbations.

Evaluation of Balance After Completion of the MRF Standing

After completing the 9 days of standing in the MRF, Subjects 1 and 2 were able to maintain balance of trunk for at least half a minute while standing in the standard wooden standing frame and having arms crossed on the chest. Both subjects were also able to perform (in a slow manner) the functional task of picking up and placing the object.

After completion of the MRF balancing, Subject 3 was able to maintain balance without arm support for a couple of minutes while Subject 4 could do the same for approximately one minute. While doing so they could also perform voluntary movements with both of their arms. They could repetitively perform the task of picking up and placing the object without compromising their balance during unsupported standing.

DISCUSSION

Multi-purpose Rehabilitation Frame

The standing and balancing environment provided by the MRF enables patient-driven therapy and neurological rehabilitation. By variation of the stiffness support and selection of the perturbation parameters the subjects are effectively in charge of their own rehabilitation process. Furthermore, this also gives them feedback on their performance. The combination of both factors was recognized as being important for positive outcome of neurological recovery and rehabilitation processes (2,6).

We chose to implement a spring-like impedance-controlled support provided by the hydraulic servo systems in both planes of movement. Even though other forms of support could have been easily tailored by means of active servo systems, there exist three fundamental reasons that favor impedance control:

1. Stable interaction between a mechanical system and a human being can be maintained at all times if the mechanical system behaves in a passive manner (12).
2. Impedance control can be realized (in future design of the MRF) by means of passive elements (variable springs), which increases safety of the device by ruling out possible malfunction of the active actuators.
3. By constraining the MRF to act as a passive system, when the only active contribution allowed is action of perturbations, the standing subject is always in charge of movement of the whole biomechanical structure.

In order to develop appropriate alternative balancing strategies after injury, we believe that it is very important that the impaired individuals with diminished balancing abilities do not use their arms (i.e., by holding onto a support) for balancing while standing. This is because when the arms are used, the control objectives posed to the central nervous system in the task of stance maintenance fundamentally change. Instead, the MRF provides support by applying forces to the pelvis, which is very similar to the support provided when the stiffness of the ankles and hips is increased. In this way the kinematic structure of the biomechanical system composed of a standing subject and the MRF remains similar to the kinematics of unsupported stance, thus enabling retraining of postural strategies needed for arm-free stance.

Besides being a tool for balance training and therapeutical standing after central or peripheral nervous system injury, the MRF apparatus has the potential to be used as a tool for objective evaluation of balancing abilities in impaired people. Should any changes occur in postural reactions of an impaired individual, either due to improved or deteriorated balancing abilities, this could be reliably identified by means of perturbations generated by the MRF, as displayed in **Figure 9**.

Preliminary Experimental Investigation of the MRF

Two qualitative changes can be observed in all four impaired subjects from the results of balance training while standing in the MRF. First, all subjects have significantly improved their balancing abilities as shown by the decreased level of support provided by the MRF in both planes of motion. Second, their posture while standing has changed from having the trunk inclined forward to a more upright posture. Equivalent conclusions can be drawn from the evaluation of balancing abilities conducted before and after the experimental standing in the MRF.

It is interesting to note that the major advancements in all subjects' performance took place during the first 3 days of the study. This indicates that the subjects learned (at least within a short-term span) how to use the residual sensorimotor abilities in order to balance during standing in the MRF within only a few sessions. The fact that Subjects 1 and 2, having relatively high lesion of spinal cord (T-6 and T-8, respectively), were able to develop alternative balancing strategies while being adequately supported by the MRF is encouraging. This indicates that a large portion of severely disabled persons might be able to benefit from standing in the MRF by improving the balancing abilities of the upper, nonparalyzed part of the body. It is also interesting to note that Subjects 3 and 4 were able to reduce the support from the initial 12 and 10 Nm/degree to only 3 Nm/degree in the course of only 3 days. This suggests that Subjects 3 and 4 already possessed balancing abilities needed to maintain arm-free stance before entering the experimental standing in the MRF. However, due to unknown reasons they were not able to make use of them. One can at this time only speculate whether the combination of controlled MRF stiffness support and the action of perturbing forces in multiple directions helped both subjects to become aware of and to further enhance their balancing abilities.

Redesign of the MRF

Balance-training sessions exposed the following two issues associated with the present design of the MRF. The first issue is related to the leg orientation of the subjects while standing in the MRF. We observed that standing subjects could make use of the MRF support also when assuming arbitrary stance apart from the parallel-leg stance. This was possible because the foam coating of the bracing system (shown in **Figure 4**) allows for a limited amount of relative movement between the bracing frame and the pelvis, which occurs when the legs and the supportive rods are not parallel.

The second issue is related to knee bracing, which was done by plastic long leg braces. This solution was entirely adequate for the two subjects with complete loss of balancing abilities of their legs, as no supraspinal control over their knees was preserved. However, such a solution prevented both subjects with diminished balancing abilities from balance training of the vertical postural axis, which is controlled by the knee joints. Knee bracing was necessary in the starting days of balance training as it enabled both subjects to concentrate only on the balancing in the sagittal and frontal planes. However, it was our subjective impression that if the subjects' knees were braced in a compliant, rather than rigid way, this could enhance balance training, as in this way the subjects would need to control their knees also. We, therefore, intend to substitute long leg bracing with a compliant strapping band, which will extend between both vertical supportive rods of the MRF, thus effectively supporting both shanks. The stiffness of the strapping band will depend on the abilities of standing subjects to control their knees. Strapping bands of various compliances could be progressively used in the course of training.

CONCLUSION

The main objective of this paper was to present a mechanical apparatus, the MRF, and its potential for neurological rehabilitation of standing in people with impaired balancing abilities. The design and operation of the MRF were driven by the concepts of motor learning that favor task-specific repetitive training, targeting both peripheral and central nervous systems (2).

Even though the MRF was evaluated only in four subjects, the preliminary results indicate that if a suitable level of stiffness support is provided, we might expect that a large portion of the impaired population will be able to improve their postural control while standing in the MRF. We think that a fall-safe and interactive MRF balancing environment made possible the observed improvement in balancing abilities of all four subjects. However, further controlled outcome studies will be necessary to demonstrate the clinical benefit of this promising device in the neurological rehabilitation of impaired individuals.

ACKNOWLEDGMENTS

The authors express their gratitude to the volunteers that participated in this study as well as to the staff of the Spinal Unit at the Viborg Hospital. Valuable assistance during the investigation provided by Dr. Ken Yoshida, Mr. Johannes van Dornik, Mr. Mike Gray, and Mr. Jan Stavnshôj is gratefully acknowledged. Further, we thank Dr. Ken Yoshida and Dr. Francisco Sepulveda for careful reading of the manuscript and useful suggestions.

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