Journal of Healthcare Engineering

Accessibility, Inclusion, and Rehabilitation Using Information Technologies

Lead Guest Editor: Antoni Jaume-i-Capó
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Contents

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Editorial

Accessibility, Inclusion, and Rehabilitation Using Information Technologies

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Social exclusion occurs when individuals, or even entire communities of people, are blocked from rights, opportunities, and resources, preventing them from fully participating in the activities of the society in which they live.

After the success of AIRTech2018 (the second edition of the International Conference on Accessibility, Inclusion and Rehabilitation using Information Technologies), we, the editors, proposed to this special issue the *Journal of Healthcare Engineering*. The purpose of this special issue is to publish recent advances in developmental accessibility, inclusion, and rehabilitation using Information Technologies. The term Information Technologies in context to this special issue refers in general to the development and use of computer systems, software, and networks in relation to issues of accessibility, inclusion, and/or rehabilitation. The articles received reflects advancements and opportunities brought about in this field through technical innovations alongside adoption and inquiry by those practicing and/or researching in this important field associated with healthcare and societal wellbeing.

The quality level of the submissions for this special issue was very high. A total of 11 manuscripts were submitted to this issue in response to the call for papers. Based on a rigorous review process, 5 papers were accepted for publication in the special issue. Below, we briefly summarize the highlights of each paper.

1. The Special Issue

Cunningham et al. address the demographic time bomb of caring for people living with dementia. Their study introduces a care platform named *Memory Tracks*, which utilizes reminiscence music and song-task association in an attempt to improve the wellbeing of people living with dementia and those caring for them. Initial indicators regarding the efficacy of the platform are presented following a mixed-method study with a small cohort living with dementia in a care home, between levels 5 and 6 on the Global Deterioration Scale for Assessment of Primary Degenerative Dementia.

Waliño-Paniagua et al. propose to analyze a virtual reality video capture training program plus occupational therapy on manual dexterity in patients with multiple sclerosis. Clinical improvements were found regarding the precision of movements, the execution times, and the efficiency of certain functional tasks in the Purdue Pegboard Test and Jebsen–Taylor Hand Function Test.

The next article is titled "Prediction of the Spinal Musculoskeletal Loadings during Level Walking and Stair Climbing after Two Types of Simulated Interventions in Patients with Lumbar Disc Herniation." Kuai et al.'s contribution reports on a study on lower back pain where spinal musculoskeletal loadings, mapped from test subjects' mocap data, inform preoperative treatment and rehabilitation planning. From this, an outcome goal was contribution toward improving capacity of spinal load sharing during activities of daily living (ADLs) after surgical intervention.

Focal vibration has shown benefits in the rehabilitation of people who have neurological conditions. Li et al. present a study that investigates the effects that focal vibration in the upper limb muscles have upon the human sensorimotor cortex. Their approach to explore this is to perform a three-phase study (before, during, and after focal vibration) and to measure the electroencephalography (EEG) response in twenty healthy male subjects. Their work presents a series of findings that contribute to what is currently known about the impact that the use of focal vibration in this setting may have upon its users.

Xu et al. propose the concept of using musculoskeletal modeling to estimate muscular states during elbow flexor resistance training for bedridden patients, and it is mainly on the discussion of computational methods. The results demonstrate that the measuring system can correctly estimate the elbow joint angle when the forearm flexes or extends in the sagittal plane.

Conflicts of Interest

The editors declare that there are no conflicts of interest regarding the publication of this special issue.

Acknowledgments

The editors would like to thank all the authors who submitted their work for consideration in our special issue, as well as all reviewers for their hard work and detailed reviews.

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Research Article

Prediction of the Spinal Musculoskeletal Loadings during Level Walking and Stair Climbing after Two Types of Simulated Interventions in Patients with Lumbar Disc Herniation

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Guest Editor: Anthony L. Brooks

Background. Low back pain (LBP) continues to be a severe global healthy problem, and a lot of patients would undergo conservative or surgical treatments. However, the improving capacity of spinal load sharing during activities of daily living (ADLs) after interventions is largely unknown. The objective of this study was to quantitatively predict the improvement of spinal musculoskeletal loadings during level walking and stair climbing after two simulated interventions. *Material and Methods*. Twenty-six healthy adults and seven lumbar disc herniation patients performed level walking and stair climbing in sequence. The spinal movement was recorded using a motion capture system. The experimental data were applied to drive a musculoskeletal model to calculate all the lumbar joint resultant forces and muscle activities of seventeen main trunk muscle groups. Rehabilitation and reconstruction were selected as the representative of conservative and surgical treatment, respectively. The spinal load sharing after rehabilitation and reconstruction was predicted by replacing the patients' spine rhythm with healthy subjects' spine rhythm and altering the center of rotation at the L5S1 level, respectively. *Results*. During both level walking and stair climbing, the joint resultant forces of the lower lumbar intervertebral discs were predicted to reduce after the two simulated inventions. In addition, the maximum muscle activities of the most trunk muscle groups decreased after simulated rehabilitation and conversely increased after simulated reconstruction. *Conclusion*. The predictions revealed the different compensatory responses on the spinal load sharing after two simulated interventions, severing as guidance for making preoperative planning and rehabilitation planning.

1. Introduction

According to the report in the literature, low back pain (LBP) continues to be one of the most serious global health problems [1] and causes tremendous direct and indirect economic costs [2–4]. One of the explanations for LBP is disc prolapse inducing nerve root compression. In most cases, the herniation could recover naturally [5], but there are still 5% to 10% of patients with disc herniation who would undergo surgery [6].

Spinal reconstruction has emerged as an effective method to restore the mechanical stability and prevent further pathological development. However, the center of rotation (COR) [7–9], which is a measure of spinal motion quality, will be altered by spinal reconstruction. It has been reported that the alternation of lumbar COR could cause considerable changes in muscle forces using a musculoskeletal model [10]. In addition, the finite element analysis has also shown that the facet forces, ligament loads, and disc stresses are strongly correlated with the location of COR [11]. In an *in vitro* study, it was found that the higher position of COR correlated with the lower facet force [12]. However, most relevant studies only focused on the single spinal functional unit (FSU) such as L5S1 [13, 14]. Additionally, the musculoskeletal model, the finite element model, and cadaveric lumbar spine were usually driven by some fixed load conditions or default constant spine rhythm. To the authors' knowledge, none of the previous studies have reported the effect of different COR locations on the load sharing of the five FSUs' joint resultant forces and multiple trunk muscle groups' activities during level walking and stair climbing.

According to Panjabi's theory [15], the stabilizing system of spine included two subsystems: (1) the spinal column and (2) the spinal muscles. Spinal reconstruction could directly change the motion characteristics of the spinal column. The strength or activation pattern of spinal muscles could be improved by effective rehabilitation. It has been found that rehabilitation for LBP patients would lead to greater improvement in the flexion relaxation response of back muscles [16] and change the muscle onsets of the lumbar erector spinae [17]. In addition, muscle activation to improve trunk stability by rehabilitation was highly related with rehabilitation strategies [17–21]. Since the origin and insertion of every muscle fascicle were around the spinal column, the resultant muscle activity was strongly associated with the spine rhythm [22]. The spine rhythm was denoted by each lumbar segmental motion contribution to the total lumbar motion. Both reconstruction and rehabilitation could improve the spinal load sharing. However, it is not clear which treatment is better to improve the spinal load sharing and to what extent the two kinds of treatment could improve the spinal load sharing.

Therefore, the objective of this study was to quantitatively predict the improvement of joint resultant forces of five lumbar intervertebral discs and muscle activities of seventeen main trunk muscle groups during level walking and stair climbing after simulated rehabilitation and simulated reconstruction for LBP caused by lumbar disc herniation (LDH). In this study, the recovery to healthy people's spine rhythm was considered as the ideal result of rehabilitation. Therefore, rehabilitation was simulated by replacing the patients' spine rhythm by healthy people's spine rhythm. The spinal reconstruction was simulated by changing the position of COR in the musculoskeletal model. Thus, we have the following two hypotheses:

(1) The spine rhythm in healthy people would be better for spinal load sharing than that in LDH patients

(2) The redistribution of lumbar joint resultant forces and main muscle groups' activities after simulated reconstruction was different from that after simulated rehabilitation

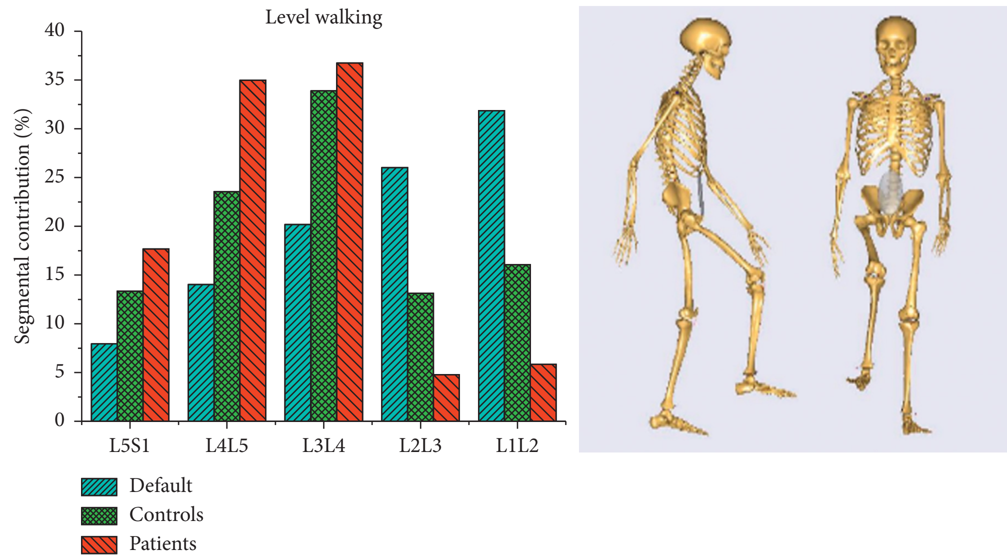
2. Methods

2.1. Subject. Twenty-six healthy male adults (age: mean 23.6 years (SD 1.92 years), height: mean 169.9 cm (SD 5.9 cm), weight: 63.5 kg (SD 8.4 kg)) and seven male LDH patients (age: mean 28.7 years (SD 4.5 years), height: mean 170.1 cm (SD 3.4 cm), weight: mean 67.4 kg (SD 5.3 kg)) were recruited for this study. The healthy controls were included if they were reported no visible motor dysfunction, no back pain, no surgery in recent one year, and no intense exercise 24 hours before trial. The patient groups were included if: (1) they had the ability to conduct basic activities of daily living such as level walking; (2) they were suffering lumbar disc herniation; (3) the herniation occurred in the lower lumbar region; and (4) the symptom had reached the criteria for surgery. In this study, the disc herniation was found to happen at the L4L5 level in three-seventh cases, at the L5S1 level in another three-seventh cases, and at both L4L5 and L5S1 levels in one-seventh cases. This study was approved by the department of orthopedics of Shenzhen Second People's Hospital in China. All the participants were given informed consent before trial.

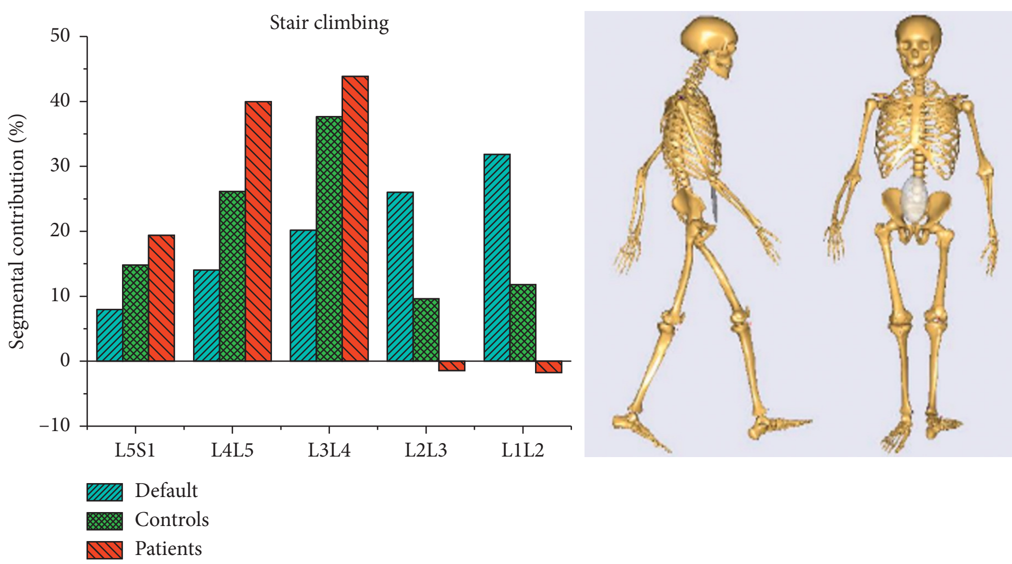
2.2. Experimental Protocol. In this study, the spinal and pelvic movements were captured by placing the optical markers on the bony landmarks. The bony landmarks included the spinous processes of the third and seventh thoracic vertebra (T3 and T7) and of the first, third, and fifth lumbar vertebra (L1, L3, and L5) and left and right posterior superior iliac spine (LPSIS and RPSIS) and the iliac crest (IC) [23, 24]. Before trials, one surgeon helped to find these landmarks and place the optical markers. Then, individuals were instructed to walk at self-selected, roughly constant speed with a moderate range of arm swing. Subsequently, participants were guided to stand on the ground in front of the staircase and then climb the staircase at a self-selected pace and place only one foot on each staircase. Before data collection, the participants had to practice the two activities until they felt they could perform them naturally.

Before trial, the participant maintained a neutral upright standing position for at least five seconds to collect the baseline data. Then, the participants performed level walking and stair climbing in sequence. Each activity was repeated three times. During the two activities, the markers were captured by Optotrak Certus motion analysis system (Northern Digital Inc., Ontario, Canada) at the sample rate of 100 Hz.

2.3. Musculoskeletal Model. In the AnyBody Managed model repository (AMMR, version 1.6) of an AnyBody Modeling system, a generic FacetJointModel was selected since it could predict the muscle forces and intradiscal forces in a redundant system. The details of the model were described and validated in the literature [25–27]. In brief, the model consisted of one pelvic segment, five lumbar vertebrae, and one lumped thoracic segment. The connection between the adjacent segment was a spherical joint which was a simplified model of the intervertebral disc. The location of each joint referred to the work by Pearcy and Bogduk [28]. In this model, there were more than one hundred muscle fascicles around pelvis and spine. These muscles were divided into several main muscle groups based



(a)



(b)

Figure 1: Three types of mean spine rhythm and schematic during (a) level walking and (b) stair climbing.

on its function, namely, rectus abdominis (RA), left and right erector spinae (ES), left and right lumbar multifidus (LM), left and right thoracic multifidus (TM), left and right oblique externus (OE), left and right oblique internus (OI), left and right psoas major (PM), left and right quadratus lumborum (QL), and left and right semispinalis (SS). All the muscles fascicles were solved as a force component using the minimum-maximum optimization algorithm and could only exert tensile force [25, 26, 29].

2.4. The Spine Rhythm and Simulation. In the spine model, the motion of every segment was driven by the spine rhythm which represented the contribution of every segment to the total spinal motion. In the AnyBody model system, the default spine rhythm was constant without consideration of the individual difference. In this study, every subject's spine model was driven by the individual spine rhythm which was determined by captured marker coordinates [23]. The features of default, control group, and patient group's spine rhythms during level walking and stair climbing were represented by the average across the gait cycle and are shown in Figure 1.

2.5. The Selection of the Optimized COR and Secondary Simulation. In this study, the position of COR was set offset from default COR for L5S1 (Figure 2). The offset was from 10 mm anterior to 10 mm posterior with an interval of 1 mm and 10 mm inferior to 10 mm superior with an interval of 1 mm. Then, the musculoskeletal model was driven to perform trunk flexion using the default lumbar spine rhythm under each offset COR. During simulation, the intradiscal forces were recorded. Finally, one position of the COR at

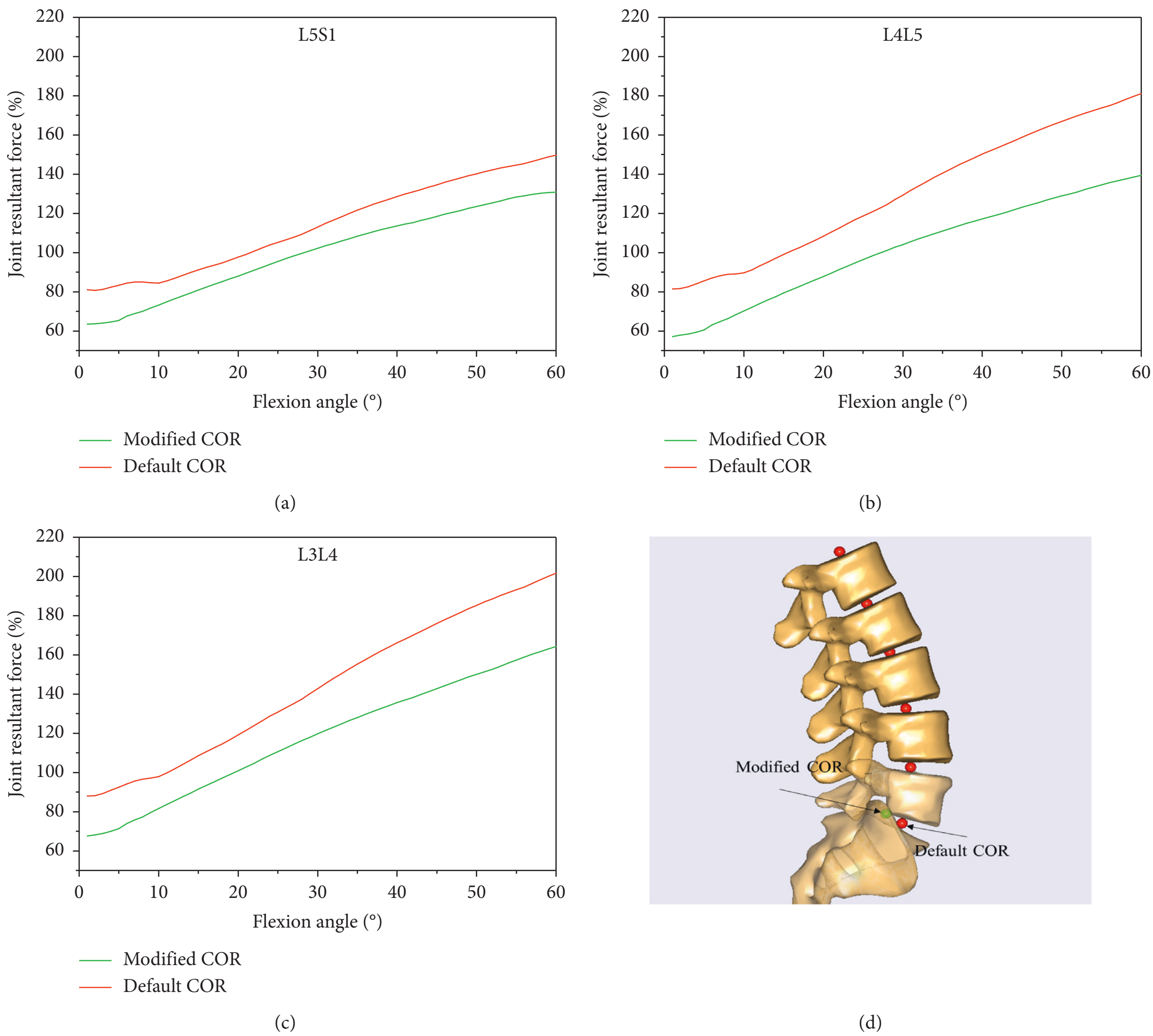


Figure 2: The position of the modified center of rotation and predicted the joint resultant forces at L3L4, L4L5, and L5S1 for default and modified center of rotation. The green line indicates the modified center of rotation. The red line indicates the default center of rotation.

L5S1 was selected because the joint resultant forces at L3L4, L4L5, and L5S1 levels were significantly decreased (Figure 2). Afterward, the musculoskeletal model was modified by resetting the default COR with new COR and then driven by every patient's spine rhythm during level walking and stair climbing.

2.6. Data Analysis. For the two ADLs, the gait cycle was defined as the time interval between subsequent heel strikes of the same leg. Then, the data of muscle activities and intradiscal forces were intercepted by the time window of the analyzed cycle. The intercepted data were time-normalized to 0–100% with 101 points. Moreover, the intradiscal forces were normalized to the body weight of every subject. The improvement at each time point was determined by the value of the variable before intervention subtracting from the value of the variable after the intervention. Data analysis was performed using custom-made programs implemented in MATLAB (the MathWorks, Inc.).

3. Results

3.1. The Effect of Two Simulated Interventions on the Joint Resultant Forces during Level Walking and Stair Climbing. Figure 3 illustrates the effect of two interventions on joint resultant forces during level walking and stair climbing. During level walking, the two interventions both decreased the joint resultant forces acting on all the five lumbar intervertebral discs. However, there were more decreases after simulated reconstruction than simulated rehabilitation. During stair climbing, all the five lumbar motion segment units showed larger reductions in joint resultant forces throughout the gait cycle after simulated reconstruction, while the improvement after simulated rehabilitation varied across the gait cycle. However, the joint resultant forces

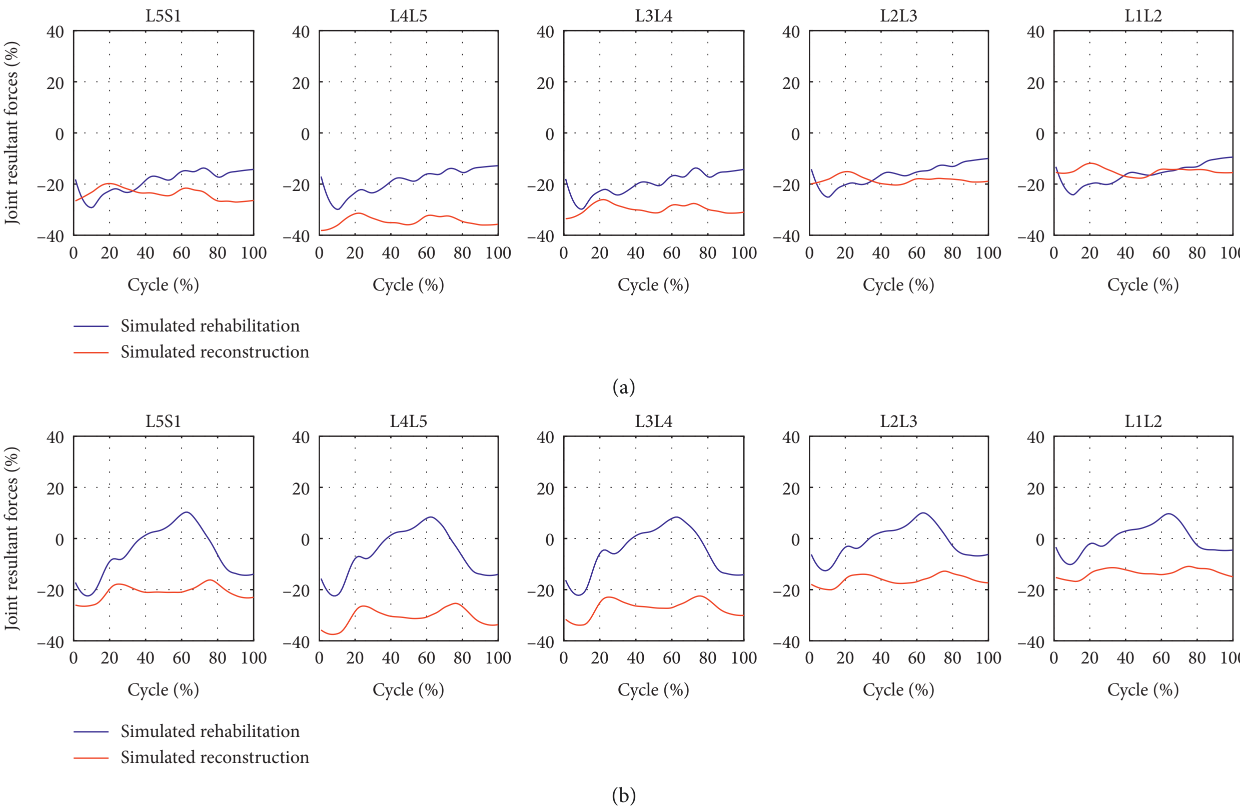


Figure 3: The improvement of joint resultant forces during (a) level walking and (b) stair climbing after the two interventions.

acting at the L5S1, L4L5, and L3L4 levels were decreased in average after simulated rehabilitation.

3.2. The Effect of Two Simulated Interventions on the Muscle Activities during Level Walking and Stair Climbing. The maximum muscle activities (MMAs) of all the seventeen muscle groups were found to possess reductions during level walking after simulated rehabilitation (Figure 4). In contrast, larger MMAs after simulated reconstruction were found in RA and two sides of ES, LM, SS, TM, IO, and EO. During stair climbing, the MMAs of all the back muscle groups and five of the nine front muscle groups were improved after simulated rehabilitation (Figure 5). In contrary to simulated rehabilitation, there were increases in the MMAs of all the back muscle groups after simulated reconstruction. In addition, seven of the nine front muscle groups showed more MMAs after simulated reconstruction.

4. Discussion

The goal of this study was to predict the effect of two simulated interventions for LDH on the intradiscal forces acting on the five lumbar intervertebral discs and maximum muscle activities of seventeen main muscle groups in the spinal region during two common ADLs.

The findings showed that there were reductions in the joint resultant forces at L5S1, L4L5, and L3L4 levels and the MMAs of the majority of the seventeen muscle groups during the two ADLs after simulated rehabilitation, supporting the first hypothesis. More decreases were found in joint resultant forces after simulated reconstruction than simulated rehabilitation during the two ADLs. In addition, the majority of the seventeen muscle groups demonstrated smaller MMAs after simulated rehabilitation but larger MMAs after simulated reconstruction. These findings supported the second hypothesis.

In the first hypothesis, the reductions of joint resultant forces were expected since decompression was one of the main therapeutic purposes for LDH. Apart from decompression, the muscle activities were also decreased after simulated rehabilitation, which was also expected since LBP could induce increases in lumbar muscle activities during functional tasks [30, 31]. The improvement in joint resultant forces and trunk muscle activities may be explained within the context of proper spine rhythm. To perform specific ADL, the central nervous system (CNS) would allocate motion for every FSU. The spinal column and musculature, which were two primary stabilizing systems in Panjabi's model of spinal stability, would respond for the motion allocation. In Arjmand et al.'s studies [22, 32], subjective alteration of spine rhythm in healthy people induced the changes in the spinal loads and muscle activities, which was in consistent with Panjabi's spinal stabilizing theory. In patients with LDH, the CNS adopted different spine rhythm strategies (Figure 1) due to subjective fear or habitual protective behavior. Likely, the spinal column and musculature exhibited adaptive response for this spine rhythm.

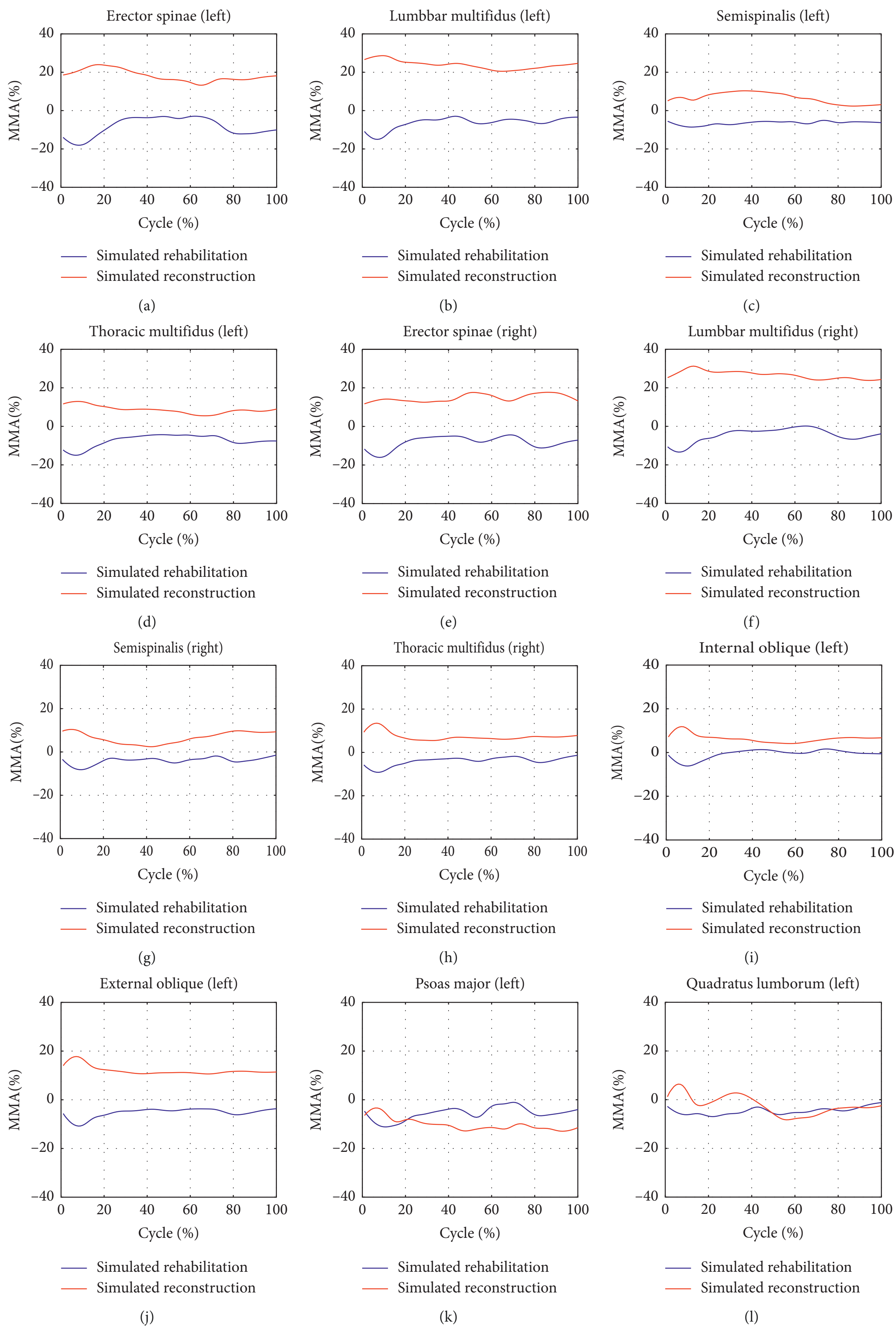


Figure 4: Continued.

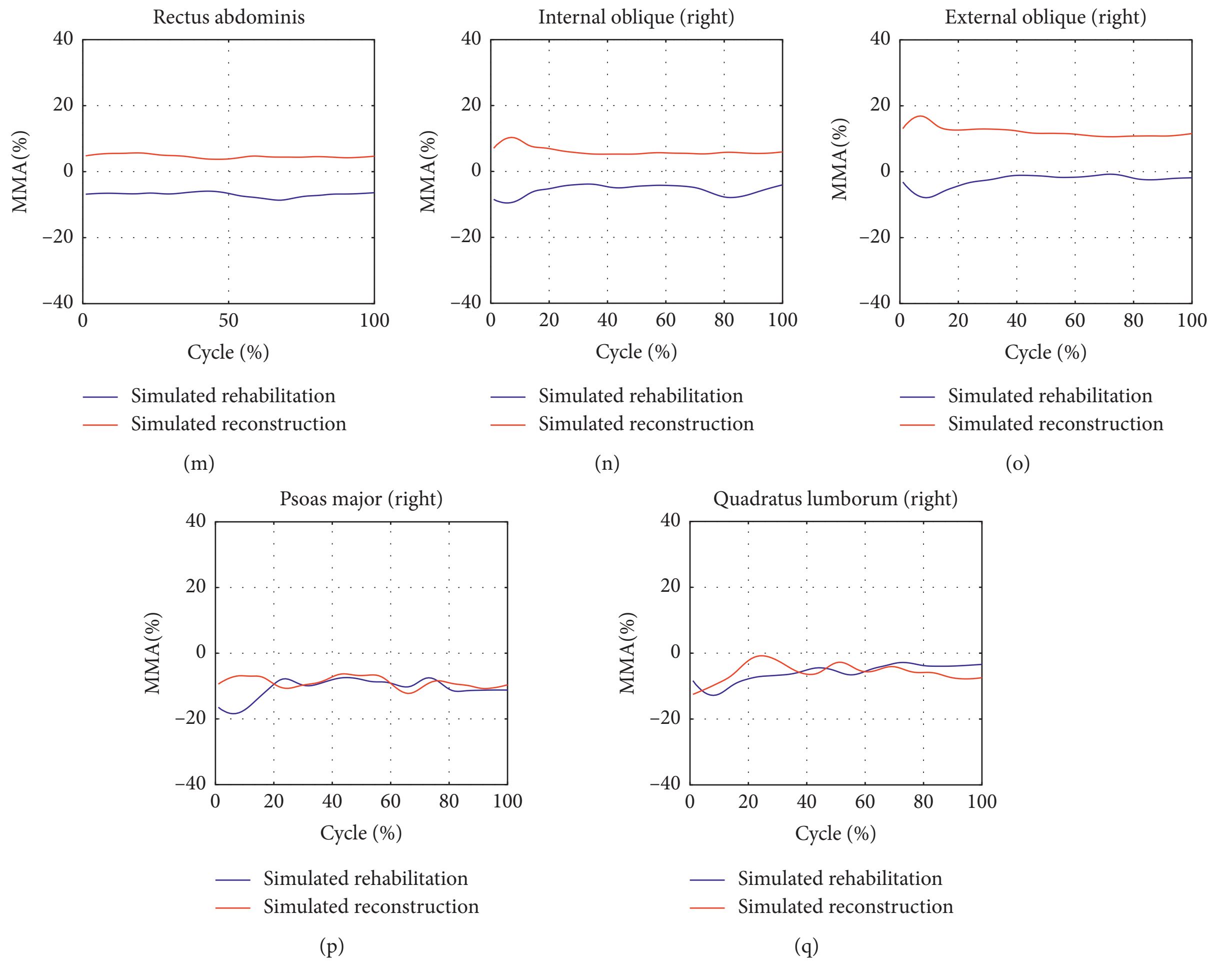


Figure 4: The improvement of maximum muscle activities of the seventeen main trunk muscle groups during level walking after the two interventions.

However, this adaptation imposed extra burdens on lumbar discs and trunk muscles because the healthy spine rhythm might be an optimal strategy for diminishing compression force [33]. Moreover, this study found that healthy spine rhythm could also lowered the burden of musculature. So, the final purpose of rehabilitation might be the recovery of the healthy spine rhythm.

In the second hypothesis, the joint resultant forces were decreased after the alteration of COR. Additionally, the effect of decompression was better after simulated reconstruction than simulated rehabilitation. The simulated rehabilitation changed the motion distribution on FSU, but the structure and motion quality of every FSU were not altered. However, the structure of FSU, which was deemed as the base of the spine, was restored after simulated reconstruction. The restoration of the spinal base might contribute to better decompression. Noteworthy was that the obvious decompression in the lower lumbar region occurred under both default spine rhythm and patient' spine rhythm even though the two rhythms are quite different (Figure 1). It could be concluded that the alternation of COR played a greater role in decompression than the alteration of spine rhythm. Different with that after simulated rehabilitation, the decreases in joint resultant forces were accompanied by the increases in MMAs of the most main trunk muscle groups, especially in back muscle groups. Han et al. [10] have also reported that the muscle forces and activation patterns could be strongly affected by the location of COR, inducing considerable higher muscle forces. In this study, the COR moved posteriorly. The lever arms of the back muscle fascicles became shorter. So, to stabilize the spinal system, it is an adaption to increase muscle forces drastically.

In closing, understanding the load sharing in the spinal region and grading the load conditions would be beneficial for the selection of treatment in clinical examination. Our findings show that both interventions could reduce the joint resultant forces. However, in consideration of huge tissue injuries and possible extra burden on muscles caused by COR offset after reconstruction, rehabilitation should be a prior intervention. Reconstruction would be advised when the larger decompression was essential. In the future study, we will assess every patient's spinal load sharing pattern and find the correlation between spinal load sharing pattern and

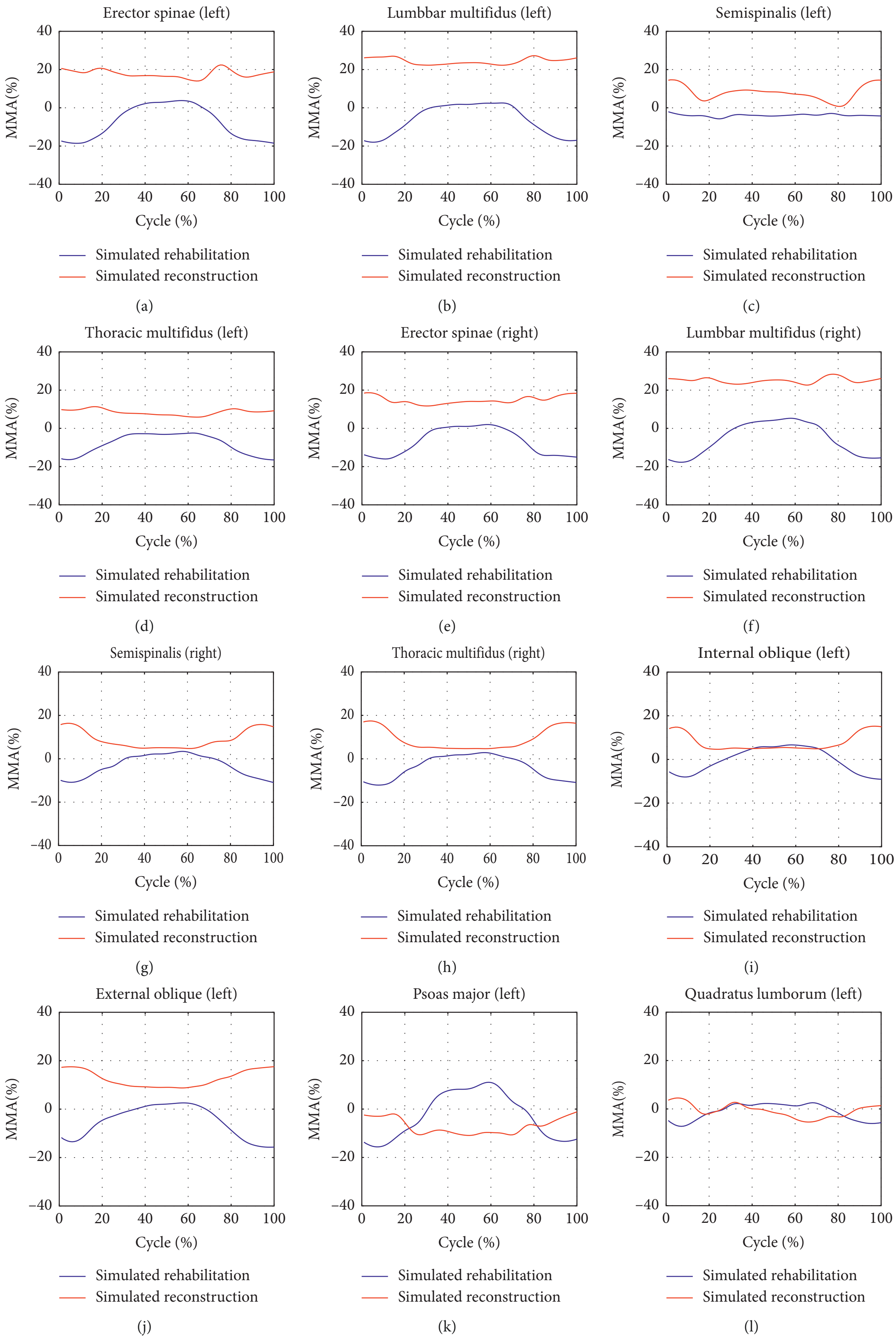


Figure 5: Continued.

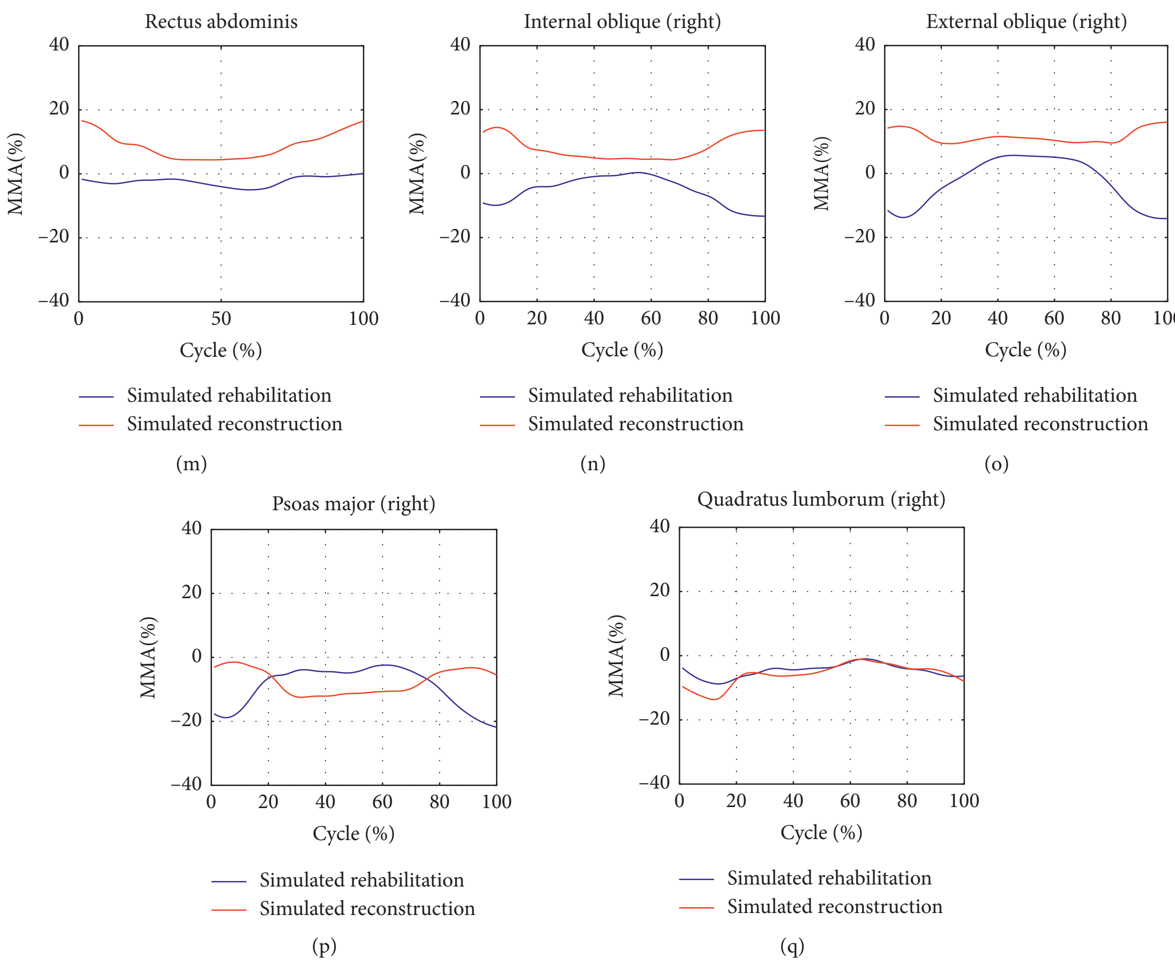


FIGURE 5: The improvement of maximum muscle activities of the seventeen main trunk muscle groups during stair climbing after the two interventions.

the therapy effect, which would guide the clinical treatment in specific.

5. Limitations

In this study, there were several limitations. Firstly, reduction in joint resultant forces was selected as the inclusive criteria for optimal COR, which might be a little arbitrary. The optimization of COR should take intradiscal forces, facet forces, muscle forces, and ligament forces into consideration. However, it was difficult to allocate weight for every variable. So, the selection for optimal COR was just a simplified method. Secondly, the prediction for reconstruction omitted the tissue injuries caused by surgery, which might affect the amplitude of some muscle forces. Thirdly, the interaction between spine rhythm and COR was not taken into consideration.

6. Conclusions

This study shows that both simulated rehabilitation and simulated reconstruction would affect the load sharing in the spine stabilizing system. Spinal loading decrease for lumbar intervertebral discs in the pathological region was predicted after both interventions. However, simulated rehabilitation reduced the muscle activities, while simulated reconstruction increased muscle activities. Considering the rapid decompression and better effects after simulated reconstruction and improvement of muscle activities after simulated rehabilitation, the combination of reconstruction and rehabilitation might be a better treatment choice for severe LDH patients. Besides, the prediction of loading characteristics during ADLs after two interventions might provide a crucial insight into the preoperative planning and rehabilitation planning.

Data Availability

The data used to support the findings of this study were supplied by Dr. Wenyu Zhou under license and so cannot be made freely available. Requests for access to these data should be made to the corresponding author Dr. Wenyu Zhou.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Research Article

Assessing Wellbeing in People Living with Dementia Using Reminiscence Music with a Mobile App (Memory Tracks): A Mixed Methods Cohort Study

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The number of people living with dementia is growing, leading to increasing pressure upon care providers. The mechanisms to reduce symptoms of dementia can take many forms and have the aim of improving the wellbeing and quality of life of the person living with dementia and those who care for them. Besides the person who has dementia, the condition has a profound impact upon their loved ones and carers. One therapeutic approach is the use of music, an area recognised as having potential benefit, but requiring further research. The present paper reports upon a mixed methods cohort study that examines the use of a musical mobile app as a way to promote song-task association in people living with dementia. The study took place in care home environments in the UK. A total of fourteen participants ($N = 14$) were recruited. Quantitative measurements were taken on a daily basis prior to, and during, use of the mobile app over several weeks. Metrics came from the complete Self-Assessment Manikin scale (arousal, valence, and dominance), and a subset of three from the Quality of Life in Alzheimer's Disease questionnaire (physical health, memory, and life as a whole). Subsequently, semistructured interviews were conducted with staff at the care home to assess the impact of the app upon their role and the residents they care for. No significant differences were found in the combined quantitative measures for the ten ($n = 10$) sets of responses sufficient to be analysed. However, the qualitative results suggest that use of the mobile app produced positive changes in terms of behaviour, ability, and routine in the life of residents living with dementia. These findings contribute to the growing body of evidence-based research in the field of musical therapies for reducing symptoms of dementia and highlight elements where further study is warranted.

1. Introduction

Dementia incidence in the United Kingdom (UK) in people aged over 65 years is over 7%, and the total number of people with dementia in the UK is forecast to reach in excess of 1 million by 2025 and over 2 million by the year 2050, with Alzheimer's disease currently being the most common subtype followed by vascular dementia [1]. On the global scale, dementia is estimated to affect over 75 million people by 2030 and more than 135 million by 2050 [2]. Identifying mechanisms to help manage the symptoms and support those living with dementia is an increasing public health priority.

In addition to the wellbeing of the person living with dementia, there is also recognition of the strains put upon their care givers. For example, work has been conducted that examines the benefits of technological interventions specifically to support care givers, which has indicated that relationships between the carer and patient can be improved as a result [3].

1.1. Music and Care. Established research has examined music as a recall trigger for autobiographical memories in patients with Alzheimer's [4], showing that there is potential to use music as a trigger when rebuilding memory. Furthermore, Cuddy et al. [5] supported these findings by studying the impact of melodies and lyrics from music on the recall of certain words in Alzheimer's and dementia patients. Both of these studies show how music can be used in memory recall and as a stimulus.

We hypothesise that there may be an opportunity to use the benefits of music as a trigger to support people living with dementia to engage with activities of daily living. The question that led to the Memory Tracks platform being developed, and the subsequent research described in this article, was posed by Anderson [6]. She suggested that reminiscence music could have a beneficial influence on those living with dementia to undertake daily tasks. The concept of *song-task association* proposed that memory could be supported by associating short pieces of music to specific daily activities for people living with dementia. Anderson suggested that the most memorable musical pieces were those heard in the earlier child development, between four and twelve years of age [6]. These pieces could become triggers associated to tasks for someone living with dementia, especially to those activities that present the greatest challenges such as eating, taking medication, or personal care. Thus, song-task association could demonstrate benefits in reducing the confusion associated with many forms of dementia and, as a result, to reduce levels of agitation or distress.

Other researchers have posited similar ideas and conducted investigations on this topic. For instance, Craig [7] provided a range of compelling arguments, mechanisms, and evaluation methods for the use of music in the field of occupational therapy, citing potential benefits to the physical, mental, and social wellbeing of the individual. More specific to the field of dementia, Raglio et al. [8] examined the impact of music therapy delivered in a traditional form of group sessions. This intervention was shown to reduce the severity of behavioural and psychiatric symptoms in those participants living with moderate to severe dementia. The present study is distinct from these other works insomuch as it was designed to examine the use of music therapy at the point of care and to test the mechanism of song-task association. In doing so, we situated our research in real-life scenarios to enable user-centred evaluation and impact measurement in daily care situations, including feedback from those with caring responsibilities. This is commensurate with a longer-term aim of Memory Tracks, where it is hoped that the platform and research will expand into supporting those living with dementia independently and outside of a care home environment.

A recent study on the amygdala highlights that new memories and association in healthy older adults can be difficult to form if an individual has a cognitive impairment [9]. In order for this association to become an automatic process, sensory experiences must be transferred from working memory or short-term memory (STM) to long-term memory (LTM) [10, 11] and be able to be recalled to working memory when needed again. For our hypothesis to be supported, an association needs to be made in adults living with Alzheimer's and dementia between a specific song and a task in their daily routine. In the process of building this association the use of explicit and implicit memory is required.

Explicit memory is a large part of language recall, and implicit memory is regularly used for word identification. Jäncke [12] explained the importance of these memory facets when building a lasting association; however, it is acknowledged that explicit and implicit memory abilities are diminished by Alzheimer's or other dementia. This could mean that building of the association, which is the primary aim of the present study, will not happen as easily or as rapidly as it would in healthy older adults [13].

The emotional behaviours associated with Alzheimer's and dementia are patterns that occur when someone living with the condition is overwhelmed with emotion [14]. These emotions include confusion, fear, panic, and anxiety, which manifest in behaviours such as lashing out, physical shaking, inability to move, crying, shouting, and screaming. These actions would be classed as emotional behaviours that this research project aims to subdue.

Zhou and Sully [15] explained how the impact of cognitive disease can change the control an individual has over their amygdala and frontal lobe, therefore causing a change in the behaviours that are controlled by the emotional rational part of the frontal lobe. This explains why emotional behaviours are heightened to a point where they impact daily tasks for people living with dementia [16]. Moretti et al. [17] reported research on frontal lobe activation and its influence on emotional behaviours. They suggested there were changes in an individual's behaviours, before and after the decrease in cognitive function has begun, which were gradually manipulated to become an irrational response to task, people, and activities. However, Jäncke [12] suggested it was a natural reaction to fear and panic as the fight or flight instinct would be prominent in Alzheimer's or dementia subjects when they were in an uncomfortable situation. Research undertaken by Wall and Duffy [18] found that behaviours of cognitive defect supported this, yet they also claimed that those reactions were only seen as emotional behaviours (and not fight or flight instinct) due to the magnitude of care which the person living with dementia was receiving.

1.2. Reminiscence Music. Previous studies have shown benefits from the use of reminiscence music, such as a reduction in depressive symptoms in those living with dementia [19]. The use of music in the treatment and care of those with physical and cognitive illness is not a new concept and has been practiced in recognisable forms since the nineteenth century [20]. A recent meta-analysis found that musical interventions are shown to have positive effects on quality of life for people living with dementia, although research in the field can be restricted because of variation in quality of the research methodology [21]. This is corroborated by a systematic review from the prestigious Cochrane Collaboration [22], which expresses limited confidence in the ability of music to have an impact upon the wellbeing of people living with dementia. This finding too is due, in part, to the variation in research quality. However, the authors articulate that additional methodically sound research in this field is important to gaining greater understanding of the true benefits of music as an intervention for those with dementia.

Hamon et al. [23] explained why music from an individual's childhood tends to be the music that can recall memories most frequently. This lends its support to the use of music from childhood in the Memory Tracks application. We hypothesise that the use of music from early years will have a strong emotional connection for the participants of the present study. It could not only strengthen the ability to form or recall a new association but also give strength to the memories and associations they already have. That, in turn, may reduce panic or fear in the participants. Koelsch et al. [24] disagreed and argued that music the individual has chosen themselves in the later years of their life may have a larger impact on their recall of certain memories. Although Koelsch et al.'s theory may have some validity, an absence of established evidence means it is difficult to validate the claim. Furthermore, Sung et al. [25] suggested that the preference for choosing music later in life may be the case for a conscious mind, with no cognitive impairment, as the person can control which emotions and memories they recall. Other research [26, 27] on music and personality would agree, although these examples of established research were conducted on healthy older adults, within the same age range as those in this study, but not on older adults living with cognitive impairments such as dementia. Often, when an individual begins to experience the onset of the later stages of dementia, they will regress to memories of childhood and their parents that music from their childhood could help to recall. Therefore, it will prompt the individual to make any emotional recall that is already present.

Autobiographical memory which is memories that relate to specific events, emotions, and other character traits that relate to a sense of identity [28] increases with age [29], with "...*access to semantic or other non-episodic information [being] preserved or facilitated.*" The development of the sense of "self" [30] is built upon by the work of Nelson [31] who theorises six levels of understanding from birth to age seven: physical, social, cognitive, representational, narrative, and cultural. Through the repetition of hearing, playing, or singing music during childhood and youth, music becomes intertwined with the sense of identity and autobiography. The "memory bump" [32] and a more recent systematic review by Munawar et al. [33] reveal that childhood memories particularly persist into old age, and musical memories are no different.

Cuddy et al. [34] demonstrated that music-evoked autobiographical memories in groups of older adults, and adults with Alzheimer's disease, have a positivity effect as defined as "...*a relative preference in attention and memory for positive over negative information.*" The study further suggests that music cues in these groups evoke (positive) involuntary memories, strengthening the case for reminiscence music in a care setting. The apparent interconnectedness of emotion, memory, music, and our sense of self was further investigated by Baird and Thompson [35] in relation to Alzheimer's disease in old age. They suggest a framework that includes various aspects of self (ecological, interpersonal, extended, and private) and that "musical self-enhancement" as detailed by Elvers [36] can form part of a definition of self. Elvers advocated that musical experiences can be used as a tool to manipulate the affective state of the individual. This feature combined with the opportunities for social bonding and the reward mechanisms offered by music facilitates such self-enhancement. Baird and Thompson [35] suggested that this definition of self is something that can be preserved, to some extent, in people with dementia.

The combination of music, emotion, and autobiography is the core principle behind the longstanding success of BBC Radio 4's "Desert Island Discs." As an archival resource, "Desert Island Discs" has been used by a study into career progression [37]; however, the potential for a systematic study related to reminiscence music is clear and one that is mirrored by the principles of the Memory Tracks application.

Reminiscence music, therefore, draws upon the emotional, narrative, and autobiographical connections made in life, particularly during formative years.

2. Materials and Methods

2.1. The Memory Tracks Mobile App. Memory Tracks is a care platform that utilises music associated to daily tasks. It is a technology platform that supports those people living with dementia, those caring for them, and their families. The application aims to help trigger memory, manage agitation, assist with care, and support daily routines through the benefit of song-task association. In its present form, Memory Tracks is an application accessed through an Android tablet device.

The Android operating system was selected as the platform for the development of the initial app. There were two reasons for this. Firstly, ease of development, the expertise available within the team, lower cost of future application programming, and flexibility with the operating system were most suited to using Android. Secondly, there was a consideration of the suitability and cost of tablet devices for the trial. The devices used were Lenovo Tab 3 730F and Lenovo Tab 7304F with front-facing speakers that offered suitable volume and clarity of the music. Rugged tablet cases and protective screens were added to ensure durability in the testing environment. With the objective to test Memory Tracks initially in care homes, the app was designed to be used offline, where WiFi Internet was not always available or desirable in this context. An additional benefit from this was that the tablets could be used in the airplane mode, thus extending the battery life of the device.

A total of 100 music tracks were preinstalled, which were pertinent to the age of the residents in the research trial. Memory Tracks established a partnership with Startle Inc., who manages the BBC Archives' Digital Music Juke Box that offered access to relevant music libraries of older recorded songs. With most of the residents in the study being 80 years and older, it required using songs primarily from the 1930s and 40s, as well as some from the 1920s and 50s. In order to identify the most memorable songs for residents, the research team accessed the online database (htttp://MusicVF.com) that listed the most popular 100 songs each year between 1900 and 2018.

For the Memory Tracks study, songs were played to groups within the study age range, and their level or recall was noted based on each individual's recognition of the music and lyrics. In the second phase of the research in Caernarfon, Wales, a number of the residents in the study spoke Welsh as their first language. A further 10 songs were added to the database that included well-known Welsh language songs and traditional folk songs.

The considerations for the application interface design were based on the principle user being a carer rather than the person living with dementia. With the initial research undertaken in care homes, it was necessary to acknowledge that professional carers would have a varied range of experience in using digital technologies. A further consideration was that using the app and completing the observation sheets would be an additional task in carers' daily work. Thus, clarity, simplicity, and speed were paramount in deploying the technology. The user interface of the app was structured around "tiles" associated to each song and task that would play the relevant music when tapped. During the early development process, these tiles used photographs to represent each task, with the objective that they would be personalised to each user. However, it became clear that the simplicity and speed of recognition for the app user needed to be improved. The tiles were subsequently changed to a standardised icon-based interface. Using the broad principles of Isotype (International System of Typographic Picture Education) [38], each task was assigned a pictorially representative icon (Figure 1).

There was additional user recognition through the use of unique colours for each song-task icon. In addition to specific tasks, such as getting up, eating, or taking medication, generic alert icons were added for tasks unique to a particular person living with dementia, along with a function to add a text description to each tile (Figure 2).

During the development process, additional functions were identified and added. A radio icon was added that would play the songs stored in the app, but omitting any songs allocated to tasks. The research team was aware that music is frequently played in care homes, in both individual rooms and common areas. During interviews with the care home staff, it was apparent that this music was usually contemporary radio and of little relevance to the residents.

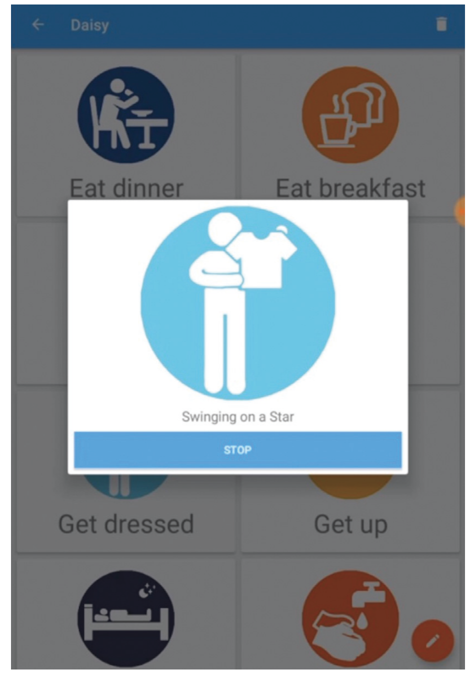

FIGURE 1: Screenshot of the mobile app with a task in progress (dressing).

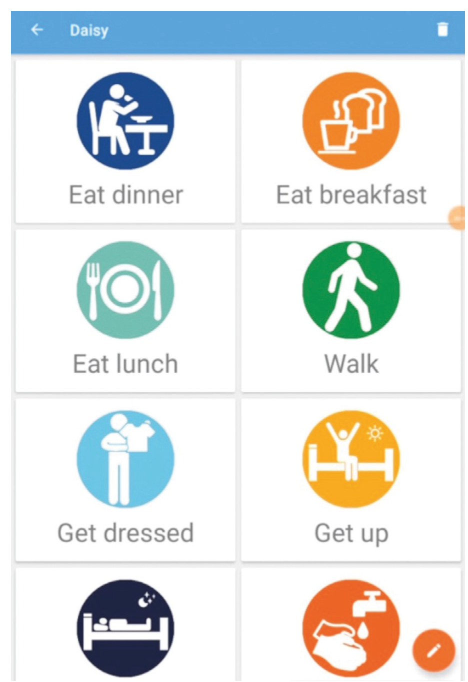

FIGURE 2: Screenshot of the mobile app showing a selection of the available tasks.

Using the radio function would allow care home residents to experience reminiscence music that could be of greater relevance, potentially offering them therapeutic benefits.

3. Research Design and Methods

The research reported in this paper aimed to investigate the effect and impact of song-task association and musical reminiscence techniques, delivered via a mobile or tablet app, upon the wellbeing of a sample from the population of people living with dementia in UK residential care, as well as the care home staff supporting them.

It is anticipated that the association, and reduction in emotional behaviours, would be set in motion by the care home resident's first recognition of a song and the memory that it recalls for them. It could be assumed from the results of Cuddy and Duffin [39] that using music as the stimulus to build the association will provide a better recall of memory and association.

The present study was designed to facilitate the investigation of the mobile app in a small sample of care home residents with dementia at the Pendine Park Care Organisation homes from sites in Wrexham and Caernarfon, both in North Wales, UK. The research followed a cohort-based approach: establishing a set of baseline data in the initial phase, introducing the mobile app as an intervention, and then subsequently following up with each cohort. During the baseline period, the participating residents and care staff continued with their normal routine. Following this, the Memory Tracks app was introduced. Care staff were instructed to use the app with the residents selected for the study in conjunction with specific daily tasks, such as getting out of bed, taking medication, getting dressed, eating lunch, or receiving personal care. Before introducing the app to the care home, the researchers discussed each participating resident with members of the care staff to identify and prioritise a set of three or four key tasks that were challenging to accomplish. Relevant music was selected for each task from the database of songs available and matched to each resident using their demographic information: principally their year of birth and where they spent their childhood.

For each participant, we selected fourteen very well-known songs from when they were aged between three and twelve years, so as to cover a ten-year window, and associated each of these songs with a daily care task that they would be engaged with. The fourteen-song selection was unique for each resident. The most common tasks were dressing, going to the toilet, taking medicine, and bathing. These associated songs were played to the resident through the app whenever the care task was being performed. Some tasks were undertaken at fixed time slots, whilst others occurred at various points during the day. After each task, residents would generally perform other activities as part of their everyday life and were also encouraged to participate in the variety of daily enrichment activities available in the home. These enrichment activities include art, music workshops, quizzes, poetry, and reminiscence, or any activity of personal interest to each individual.

Music was played using the speakers built into the tablet provided to each of the participants. Headphones were not used so as to avoid complications associated with the additional equipment and isolation from their surroundings. It was recognised that when tasks were performed in communal areas or social settings, this may present an interaction effect with other residents at the home. However, an underlying intention in the study was to examine Memory Tracks in an ecologically valid scenario; hence, this was not controlled by the design of the research.

Care staff subsequently reported that, in communal areas, and particularly at meal times, they chose the music of the resident who was most likely to find that task difficult. This was done with the intention of providing a better environment for all concerned, with other residents often joining in. The music was played at a relatively low volume. In most cases, residents dined in small groups of two to four people or in their own room if that was their preference. If it was noted that the music bothered other residents, staff would relocate to a quiet area or a participant's room and continue to use the app there, but this was a very rare occurrence as most other residents enjoyed and responded positively to having the music playing, mainly by singing along or humming to the track.

Two cohorts of participants from each site took part in the study. Prior to the app being introduced, the researchers visited the care home to train the care team in the use of the Memory Tracks software platform. In Wrexham, the residents were observed for approximately three weeks before the mobile app was introduced and then for four weeks whilst using the mobile app. In Caernarfon, the same process was repeated for two weeks and four weeks, respectively. During the period where the app was being used, care staff were asked to play the relevant songs when the associated care tasks were being performed. Quantitative data were collected over the course of the study period, and qualitative data were captured at the end of the study period.

In terms of quantitative, observational data were collected daily by the care staff using a paper-based form and with a small number of questions. The care staff received a training session about the observation form prior to the start of the study. A deliberate design decision was taken to make the form a simple and fast process to complete, so as not overly to distract the staff from their usual duties. Six measures were taken each day. Three of these measurements used the Self-Assessment Manikin (SAM) pictorial scale [40], using ordinal intervals between 1 and 9, to capture each resident's emotion on the dimensions of *valence* (happy to sad), *arousal* (excited to calm), and *dominance* (dependent to independent). The other three measures were questions taken from the Quality of Life in Alzheimer's Disease (QOL-AD) questionnaire [41], measured using ratings of "poor," "fair," "good," and "excellent," to assess each resident's *physical health*, *memory*, and *life as a whole*. One set of measures was recorded for each participant each day during the study. The observations were scheduled so as to gain a balance of measurements taken at different times during the day (morning, afternoon, and evening).

Following the end of each study period, qualitative data were obtained by conducting a set of semistructured interviews with the care staff. The prompts used during the interview were designed to elicit responses from care staff on several topics: setting up the app with the participant, the app's ease of use, impact upon the care staff's own work, and perceived impact of the app upon the residents, along with any additional comments or issues. Interviews were conducted on the care home site and had a mean duration of 14 minutes and 48 seconds. There were always two or more members of the research team present. Some interviews were with small groups of care staff, and the others were with individuals. After the data were collected, the interview recordings were transcribed by members of the research team, then double and triple checked, and subsequently analysed using thematic analysis [42], which resulted in main themes and subthemes being formed from recurring statements or sentiments in the study.

4. Participants

The selection of participants was undertaken with the advice of the staff at Pendine Park Care Organisation. In doing so, participants could be identified based upon their current physical and cognitive characteristics, including the level of dementia with which they are living, resulting in a convenience sample. Participants were residents recruited from two care homes in the Pendine Park group. Participants were living with dementia, were typically between levels 5 and 6 on the Global Deterioration Scale for Assessment of Primary Degenerative Dementia [43], and were included in the study to reflect different types and stages of dementia. Each individual was selected by the registered manager and care team at each site. The balance of the individuals participating in the study cohort was those with Alzheimer's disease (60%) and vascular dementia (40%). The care team selected a mix of residents, some of whom were recognised as enjoying music and others that had difficulties engaging with their routine tasks, such as bathing and eating. Informed consent was obtained either from each participant directly or via an appropriate designated person [44]. Where the legal responsibility of care lays with a family member or guardian, a discussion was held, and they were provided with formal information about the study before consent was requested. In other participants, where the care home management held this responsibility, the same process was followed. In order to safeguard participants, care staff were instructed to take the intervention away if it caused distress or negative behaviours.

In the Wrexham component of the study, a total of six residents were recruited. For the portion of the study based at the Caernarfon site, a total of eight residents were recruited, although only four of these fully completed the quantitative part of the study. Overall, there were 5 male and 9 female participants with a mean age of 84.60 (SD = 8.69) years, with an overall age range of 69 to 97 years. Participants were mainly living with diagnoses of vascular dementia or Alzheimer's disease and had a mixture of idiosyncrasies and conditions. In many cases, these could be problems with compliance in performing everyday tasks, such as washing, eating, and dressing, or in communication. In some cases, this could relate to being physically vulnerable and at risk of falling or could include mood swings and aggressive behaviours.

5. Results and Discussion

5.1. Quantitative Results. Data were collected at the two sites for the periods described earlier in Methods and Materials. Upon receipt of the paper-based observation sheets and their transcription to digital format, it became apparent that there were occasional inconsistencies and missing data, particularly at the Caernarfon site where there were only usable data collected for four of the eight participants. This was further compounded by the duration of data collection being slightly different at each site. Consequently, given the relatively small number of participants ($n = 10$) and rather than applying a method to interpolate or impute missing values, the decision was made to use mean values for each participant, treating them as a single cohort, before and during their use of the mobile app, for each of the six quantitative measures. Since the main aim was to investigate any difference within subjects over the course of the research, all of the data collected from the participants were able to be utilised, albeit in a descriptive form.

To investigate any effect of the mobile app intervention upon the participants, a one-way MANOVA with repeated measures was performed upon participants' mean values for the six measures. The statistical test showed no significant effect (Wilks' lambda $F(6, 4) = 0.29$, $p = 0.33$), indicating that the use of the mobile app had neither a positive nor a negative impact upon the six combined indicators of participants' wellbeing. Although it was not a normal process following the MANOVA outcome, given the small number of participants and combination of indicators, univariate analysis for each of the six measures was performed. Two of the measurements showed significant results: *valence* ($F(1, 9) = 7.232$, $p < 0.05$) and *physical health* ($F(1, 9) = 6.000$, $p < 0.05$). Whilst these findings must be viewed with caution, they provide an initial indication that the use of the mobile app may have positive benefits for users.

As shown in Figure 3, participants' scores for emotional valence decreased, on average, from 4.22 to 3.84. Recalling that the scale for valence operated on a value of 1 being labelled *happy* and 9 labelled *sad*, this movement is towards the positive valence end of the scale.

Figure 4 shows participants' scores for the ratings of physical health increased with the use of the mobile app, on average, from 2.20 to 2.60. Recalling that the scale for physical health operated on a value of 1 being labelled *poor*, 2 labelled *fair*, 3 labelled *good*, and 4 labelled *excellent*, this movement is towards the positive physical health end of the scale.

Given the findings from the inferential analysis, and cognisant of the number of participants, there is value in analysing the data on a descriptive level. For the questions taken from the QOL-AD relating to factors of physical health, memory, and life as a whole, mode responses are referred to. These were obtained by calculating the mode of all of the observations, per participant, before Memory Tracks was introduced and again for the period where Memory Tracks was present. By examining the individual participants, we can make the following observations:

(i) There was no definitive change on the SAM *arousal* scale (5/10 moved towards "Calm," and 5/10 moved towards "Excited").

(ii) 8/10 residents showed small changes in terms of *dominance* (moving towards the "Independent" end of the scale).

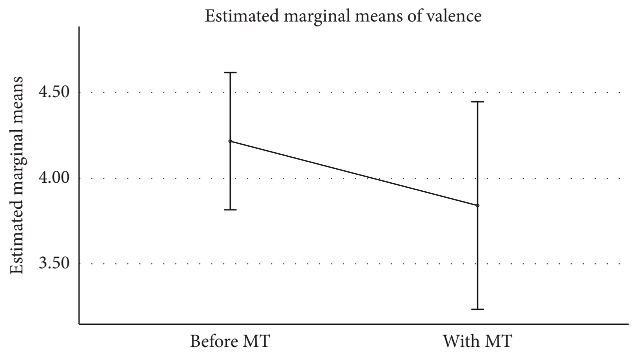

Figure 3: Valence ratings before and during use of the mobile app (Memory Tracks). Error bars: 95% CI.

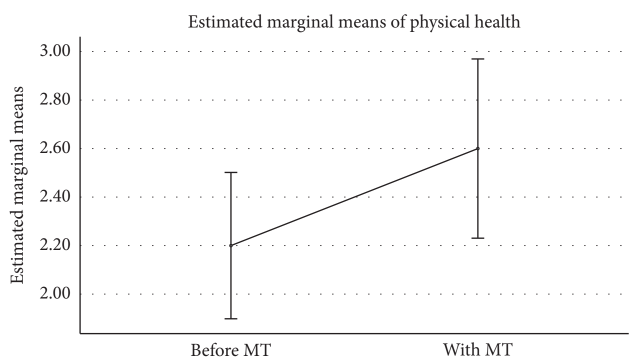

Figure 4: Physical health before and during use of the mobile app (Memory Tracks). Error bars: 95% CI.

(iii) The mode response in 4/10 residents increased one position from "Fair" to "Good" for the QOL-AD question "How would you rate the resident's physical health today?" In the remaining six residents, the mode of their scores remained the same.

(iv) The mode response in 2/10 residents increased one position from the ratings received prior to Memory Tracks being introduced for the QOL-AD question "How would you rate the resident's memory today?" One moved from "Poor" to "Fair" and the second from "Fair" to "Good." In the remaining eight residents, the mode of their scores remained the same.

(v) The mode response in 3/10 residents increased one position from "Fair" to "Good" on the scale for the QOL-AD question "How would you rate the resident's *life as a whole* today?" In the remaining seven residents, the mode of their scores remained the same.

5.2. Qualitative Results. Themes were found through the quotes and reoccurring benefits and limitations highlighted about the mobile app that were repeated in each of the interviews. The themes identified are *behaviour*, *ability*, *impact*, *routine*, and *music*, with subthemes providing some additional clarity and definition to the main themes.

5.2.1. Theme: Behaviour. Music can influence mood and behaviour in a significant way. Care staff who took part in the interviews believed that the behaviours changed due to the mood of the individual shifting. This could be seen in some of the examples that were given by the care staff such as

(i) "*. . .he would have known what the music was for but it did calm him down really*"

(ii) "*Quite nice for us not to have her screaming*"

Sundown syndrome [45] was mentioned a number of times by interviewees. This is when a resident's mood becomes negative due to the time of the day. However, music whether it was being played in the lounge or via the app seemed to help this mood from becoming too dark, especially at bedtime.

5.2.2. Theme: Ability. Reduction in physical and cognitive abilities is often seen in people living with dementia, especially when compounded by the natural ageing process. The presence of music via the app was perceived as encouraging some participants to unlock abilities that had deteriorated. For example, one participant was able to feed herself once the app was available at meal times. The theme reoccurred in a number of interviews with care staff:

(i) "*I know* [participant name] *loves it*, *downstairs*, *she likes the memory of it*"

(ii) "*When she tells me she needs the toilet she grabs the tablet as if to tell me 'let's go*"

Whilst there were improvements in physical and cognitive abilities for some of the participants, a third element of ability appeared to develop, that of independence. It appeared that the app allowed some participants to do small tasks independently that they had not been able to before, thereby improving their motor skills and memory of doing it prior to the onset of their condition:

(i) "*Yeah, she independently eats her meals and drinks*"

5.2.3. Theme: Impact. In the data where this theme reoccurred a number of times, it appeared that there was only an impact on some of the residents. These participants tended to be those who had a previous interest in music, or had worked with, or played music when they were a younger:

(i) "[participant name] *went back to her agitated mood because we didn't have the tablet there*"

(ii) "*It was beneficial for* [participant name] *but not as much for* [another participant name]"

From the data, it appeared that any impact that the app had was positive, with the exception of one resident. This participant in the study recognised a song that had an unpleasant memory for her. In this instance, the song was removed. Although it was a negative experience for the participant in question, this finding shows another form of impact that music as a stimulus for recall can have and supported the requirement for new associations to be created in place of older ones.

5.2.4. Theme: Routine. Routine was an expected theme to develop, and there were questions in the interviews that sought to determine its presence. The app was created to focus on using music through the care routine of a resident. There were two facets to the theme of routine—one was the way that the app fitted into the care staff's daily routines and the other was the way playing music from the device influenced the resident's routine:

(i) "[participant name] *loves it, when she is having breakfast and dinner*"

(ii) "*I would actually make time, it doesn't matter how busy I am I would always make time to actually use this (the app) with them*"

(iii) "*. . .with* [participant name] *it relaxed him and he was calm, you get the tasks done quicker*"

5.2.5. Theme: Music. Music is one of the key components and concepts in this research; therefore, it was strongly anticipated that it would be an overall theme resulting from the qualitative data. There were a variety of ways in which the music theme occurred in the data—from the care staff learning the words of the songs and singing along with the residents to the type of music that the residents would respond to:

(i) "*I think the type of music would have helped too as* [participant name] *like reggae music*"

(ii) "*He said a couple of times 'Oh I knew this song when I was a boy*"

(iii) "[participant name] *absolutely loves music*"

As established literature has shown, music therapy has demonstrated significant improvement for health and wellbeing over and over again. Although the results of the present study show once again that music can impact the wellbeing of participants, it has also produced new themes and quantitative data that suggest music can be used as a daily aid in care, not just as a therapy or for social activity. More research with a larger sample would be needed with further research to support fully the benefits of the Memory Tracks app as a daily aid in music task association. From the research presented here, it can be seen that some residents are starting to build a foundation association with the app and music and slowly associating that music with their daily tasks. However, for such a specific association to be made, it may take a longer time than the duration of our study.

6. Conclusions

Studies in music and memory have shown how there may be a reserve of memory specifically for music, and this may be why music can trigger autobiographical connections or associations in memory despite a cognitive impairment. It was the aim of this research project to consider the impact of music not only on building association but also on the resident's wellbeing. This was clear to see when care staff explained how certain residents were not as agitated or were participating in sessions and tasks where they had not previously done so.

The quantitative results here are best considered in partnership with the qualitative analysis, to form a more holistic view of the impact that Memory Tracks had upon the residents of Pendine Park. The individual nature of each participant, their background and demographic, may well impact their amenability to using reminiscence music, and this may account for the indications that the mobile app has a small, positive effect upon some residents but not on others. The quantitative results provide early indications that the mobile app may have a beneficial impact, but a larger study is required to provide a better picture, and this is a priority for future research using the app, although recruitment of a large cohort and maintaining control over the data collection routines are shown to be problematic in such a study, though not insurmountable.

This research has shown that residents may make a general association between the Memory Tracks app and the music that is played. This would be a general association that shows a positive impact and indication that a specific connection between a song and a task could be made. El Haj et al.'s research [46] on the association and memory supports this process and also highlights why music has such a strong stimulus. It identifies that people regularly tie their emotions to music and, as a by-product of this, to memories.

More generally, extensions of the present work, if successful, may produce benefits in people living with dementia across the full spectrum of the condition, from those with primary care needs to those still living independently. In the future, we anticipate that the work will be extended to see if benefits can be translated to other neurological conditions, such as stress, depression, and autistic spectrum disorder.

One avenue for future work would be to focus upon the specific effects of music therapy in people living with dementia through the use of neurophysiology techniques. Such an approach is attractive since it would give an alternate and objective way to measure the effects of music and song-task association, as well as the ability to observe these effects in real time. An example of such an approach exists in the work of Mitterschiffthaler et al. [47], who used functional-magnetic resonance imaging (f-MRI) to investigate positive and negative affective states in response to listening to Western classical music. Similarly, Rojo et al. [48] used f-MIR and transcranial magnetic stimulation (TMS) to evidence that a programme of music-supported therapy was a ". . .useful neurorehabilitation tool in patients with chronic stroke and leads to neural reorganization in the sensorimotor cortex." Both of these articles lend credence to the suggestion that music therapy induced demonstrative brain responses and that these may have neurotherapeutic benefits.

There are further technology upgrades planned to the Memory Tracks app. A greater understanding of the application after the initial study has indicated the following developments:

(i) Improvements in the music selection process: the aim is for the app to identify possible reminiscence tracks automatically, based on the birth date and location of the early years of the subject living with dementia. As memorable music is identified for each subject, a recommendation engine will suggest further songs.

(ii) Improved survey data collection: in future iterations, the observation sheet will be included in the app, with a daily prompt to complete the information. This will reduce the additional tasks for carers and support easier analysis for larger sample groups.

Further technology developments are planned as part of the Memory Tracks enterprise. These include the addition of the sensor technology to add contextual and behavioural triggers. Additionally, the use of machine learning will be implemented to predict typical behaviours and send alerts to carers where behaviours are abnormal.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

Stuart Cunningham, Mark Brill, Harry Whalley, Rebecca Reid, and Richard Picking declare that there are no conflicts of interest regarding the publication of this paper. Gordon Anderson is a Director of Memory Tracks Ltd. Sarah Edwards is an employee of Pendine Park Care Home.

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Research Article

Effects of Focal Vibration over Upper Limb Muscles on the Activation of Sensorimotor Cortex Network: An EEG Study

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Studying the therapeutic effects of focal vibration (FV) in neurorehabilitation is the focus of current research. However, it is still not fully understood how FV on upper limb muscles affects the sensorimotor cortex in healthy subjects. To explore this problem, this experiment was designed and conducted, in which FV was applied to the muscle belly of biceps brachii in the left arm. During the experiment, electroencephalography (EEG) was recorded in the following three phases: before FV, during FV, and two minutes after FV. During FV, a significant lower relative power at C3 and C4 electrodes and a significant higher connection strength between five channel pairs (Cz-FC1, Cz-C3, Cz-CP6, C4-FC6, and FC6-CP2) in the alpha band were observed compared to those before FV. After FV, the relative power at C4 in the beta band showed a significant increase compared to its value before FV. The changes of the relative power at C4 in the alpha band had a negative correlation with the relative power of the beta band during FV and with that after FV. The results showed that FV on upper limb muscles could activate the bilateral primary somatosensory cortex and strengthen functional connectivity of the ipsilateral central area (FC1, C3, and Cz) and contralateral central area (CP2, Cz, C4, FC6, and CP6). These results contribute to understanding the effect of FV over upper limb muscles on the brain cortical network.

1. Introduction

In the past few years, more effort has been paid to studying the effects of focal vibration (FV) at a high frequency (50~120 Hz) and with a low amplitude on the rehabilitation of neurological diseases, such as stroke, spinal cord injury, multiple sclerosis, and cerebral palsy [1]. As for patients with stroke, FV can improve various abilities and functionalities, including walking [2], postural sway and gait ability [3], motor performances of reaching movement [4], stability of the proximal arm [5], and reducing spasticity [6, 7]. As for patients with spinal cord injury, FV reduced spasticity [1] and elicited stepping movements [8]. Additionally, research indicated FV can also contribute to the improvement of movement control in patients with multiple sclerosis [9].

The neurophysiological mechanism underlying how FV benefits the recovery of motor function for patients with neurological diseases has been explored mainly in experiments with healthy subjects. At spinal cord level, some studies have shown that FV induced the firing of muscle spindle primary endings (Ia afferent fibers) [10–12]. At the cortical level, studies using transcranial magnetic stimulation (TMS) showed that FV enhanced the excitability of motorcortical representation of vibrated muscle [6, 13]. Besides, some researchers also have proved that vibrotactile stimulation on the palm or fingers caused the activation of primary motor cortex (M1), primary somatosensory cortex (S1), and secondary somatosensory cortex (S2) using functional magnetic resonance imaging (fMRI) [14–18]. However, how FV applied to other body sites influence the activation of sensorimotor cortex has not been fully studied.

Electroencephalography (EEG) is an electrophysiological method to record the electrical activity of the brain. The rolandic alpha rhythm (sensorimotor "mu" rhythms) concentrates mainly in the somatosensory postcentral gyrus, while the rolandic beta rhythm (sensorimotor beta rhythms) mainly originates in the precentral motor cortex [19, 20]. It was well accepted that event-related desynchronization (ERD) (the decrease of power) over the sensorimotor areas represented the activation of the sensorimotor cortex. On the contrary, event-related synchronization (ERS) (the increase of power) reflected the deactivation of the sensorimotor cortex [21, 22]. Some EEG-fMRI studies also showed that the decrease of EEG power was related to activation of the sensorimotor cortex [19, 23–25]. As for functional connectivity, it can reflect the level of synchronization between the signals of different scalp regions, as well as the topological and dynamics properties of information flow between different brain areas [26, 27]. Recently, it has been used as a biomarker to investigate the mechanism of functional recovery in patients with neurological diseases [28–31].

In this study, we aimed to study the effect of FV applied over left biceps brachii on the sensorimotor cortex during FV and after FV. We recorded the EEG activity before FV, during FV, and 2 min after FV. Then, we analyzed the changes of relative power at C3 and C4 and functional connectivity of the central region (FC5, FC1, FC2, FC6, C3, Cz, C4, CP5, CP1, CP2, and CP6) in the alpha (8–12 Hz) and beta (12.5–30 Hz) band.

2. Materials and Methods

2.1. Participants. Twenty male right-handed healthy subjects with a mean age of 26 years (±0.6 years) were recruited in Tsinghua University in this study. All subjects were informed about the procedure of the experiment. All the subjects gave written consent prior to the experiment. The study was approved by the institutional ethics committee.

2.2. Experimental Setup. All the participants were informed to have a good rest one day before the experiment in order to minimize drowsiness. During the experiment, each subject was seated in a comfortable chair with both arms on the armrest and their hand supinated so that their upper limbs were relaxed. FV with frequency at 75 Hz and amplitude at 1.2 mm was produced by a mechanical vibration device with a vibration head (YS-889, Jialemei Health Care Co., Ltd., Taiwan, China), as shown in Figure 1. The mechanical vibration device was operated at a power frequency of 50 Hz. FV was applied perpendicularly over the muscle belly of biceps brachii in the left arm lasting for three minutes. During the EEG recording, subjects were asked to minimize head movement, eye movement, body movement, and chewing and were required to wear earplugs to reduce external noise and vibration noise. Based on the recommendation to use eyes-closed resting EEG as a baseline for tasks without visual stimuli [32], all the subjects were asked to keep their eyes closed during this experiment. Specifically, EEG was collected in the following three phases: (1) before FV (baseline: before-FV), the resting state EEG was recorded with the eyes closed for 4 min; (2) during FV (during-FV), EEG were recorded with the eyes closed for 3 min of vibration; and (3) after FV (after-FV), EEG were recorded with the eyes closed for 3 min, starting at 2 minutes after the termination of FV.

Figure 1: Illustration of the experimental setup.

2.3. EEG Recordings. EEG signals were recorded with ANT hardware and software (B.V., Enschede, the Netherlands) from 32 Ag/AgCl electrodes mounted in a commercial WaveGuard EEG Cap (Eemagine Medical Imaging Solutions GmbH, ANT Advanced Neuro Technology) and positioned over the whole scalp according to the international 10–20 system, as well as two electrodes on the left and right mastoids. A ground reference electrode was located between the Fpz and Fz electrode, and the reference electrode was located at the Cpz electrode. The sampling rate was set at 1000 Hz. Electrode impedances were kept below 5 kΩ.

2.4. EEG Signal Analysis

2.4.1. Signal Preprocessing. The EEG signals were preprocessed in EEGLAB 14 (EEGLAB toolbox, Swartz Center for Computational Neurosciences, La Jolla, CA; http://www.sccn.ucsd.edu/eeglab). Data were divided into segments of 2 s. Artifacts were visually detected. The data were referenced to the common average reference. The power line noise 50 Hz was removed. A band-pass filter was set between 0.5 Hz and 50 Hz. The Welch method (pWelch algorithm, an overlapping 1-second hanning window, no phase shift) was applied to compute the power spectral density of each epoch (2 second duration, 2000 data points) using a 0.5 Hz frequency resolution, and all the epochs were then averaged.

2.4.2. Relative Power Analysis. In this study, relative power was estimated in the two frequency bands: alpha (8–12 Hz) and beta (12.5–30 Hz). The relative power RP(·) was calculated as follows:

$$\mathrm{RP}(f_1, f_2) = \frac{\int_{f_1}^{f_2} \mathrm{PSD}(f_1, f_2) df}{\int_{f_1}^{f_2} \mathrm{PSD}(0.5, 50) df}, \quad (1)$$

where f_1 and f_2 indicate the low and high frequency of the specified frequency band, respectively. PSD(·) indicates the power spectral density.

Alpha and beta motor-related power desynchronizations (MRPD) at C3 and C4 electrodes were used to indicate the activation of primary sensorimotor cortex [33]. MRPP was calculated as follows:

$$\mathrm{MRPD}_{\text{during-FV}} = \frac{\mathrm{RP}_{\text{during-FV}} - \mathrm{RP}_{\text{baseline}}}{\mathrm{RP}_{\text{baseline}}}, \quad (2)$$

$$\mathrm{MRPD}_{\text{after-FV}} = \frac{\mathrm{RP}_{\text{after-FV}} - \mathrm{RP}_{\text{baseline}}}{\mathrm{RP}_{\text{baseline}}}, \quad (3)$$

where $\mathrm{RP}_{\text{baseline}}$, $\mathrm{RP}_{\text{during-FV}}$, and $\mathrm{RP}_{\text{after-FV}}$ indicate the relative power before FV, during FV, and after FV, respectively. The negative or positive values reflected alpha (beta) movement-related power desynchronization or synchronization, respectively.

2.4.3. Functional Connectivity Analysis. In this study, functional connectivity was estimated using imaginary coherence, which reduced overestimation biases that exist in many other measures, such as phase locking value, absolute coherence, and synchronization likelihood [34–36]. Due to the common reference, cross-talk, and volume conduction, these measures generated spurious interactions with no time lag. Imaginary coherence was expressed as the imaginary part of coherency $C_{ij}(f)$, which was defined as the normalized cross-spectrum:

$$C_{ij}(f) = \frac{S_{ij}(f)}{\left(S_{ii}(f)S_{jj}(f)\right)^{1/2}}, \quad (4)$$

where $S_{ij}(f) \equiv \langle x_i(f)x_j^*(f)\rangle$ is the cross-spectrum. $x_i(f)$ and $x_j(f)$ indicate the complex Fourier transforms of the time series $\hat{x}_i(t)$ and $\hat{y}_j(t)$ of the channel i and j, respectively. $\langle\rangle$ indicates expectation value and $*$ indicates complex conjugation. Expectation value was estimated as an average over all the segments.

In this study, the functional connectivity of the central region (FC5, FC1, FC2, FC6, C3, Cz, C4, CP5, CP1, CP2, and CP6) was calculated.

2.5. Statistical Analysis. The statistical analysis was performed by SPSS Statistics 20. In the analysis of relative power, two-way repeated measures analysis of variance (ANOVA) was used. Before two-way repeated ANOVA was performed, the Shapiro–Wilk test was used to determine if all the data sets of relative power were well-modeled by a normal distribution. The ANOVA factors included the main factor condition (before FV, during FV, and after FV) and the main factor electrode (C3 and C4). If the main factor condition or electrode showed a significance, a paired-sample t-test was then performed. In the statistical analysis of functional connectivity, there were a large number of tested channel pairs ($C_{11}^2 = 55$). To make sure the probability of one or more null hypotheses incorrectly rejected, false discovery rate (FDR) correction was performed. The Type I error was set to 0.05. Pearson's correlation analysis was performed between alpha MRPD and beta MRPD during and after FV.

3. Results

3.1. Relative Power Analysis. In the alpha band, the Shapiro–Wilk test showed relative power at C3 ($p = 0.991, 0.867$, and 0.438) and C4 ($p = 0.126, 0.097$, and 0.156) during three phases, before FV, during-FV, and after-FV was normally distributed. Two-way repeated-measures ANOVA showed the interaction electrode × condition ($F(2, 38) = 1.137$; $p = 0.331$) and the main factor electrode ($F(1, 19) = 2.480$; $p = 0.132$) were not significant, while the main factor condition ($F(2, 38) = 4.718$; $p = 0.015$) was significant. A paired-sample t-test for the relative power at C3 and C4 showed a significant decrease during FV (one tailed: $p = 0.0095$ and 0.0075) and after FV (one tailed: $p = 0.0145$ and 0.037) compared to before-FV. After the Bonferroni correction, the relative power of C3 and C4 during FV showed a significant decrease (one tailed: $p = 0.019$ and 0.015), whereas the relative power of C3 after FV showed a significant decrease (one tailed: $p = 0.029$) (Figure 2).

In the beta band, the Shapiro–Wilk test showed relative power at C3 ($p = 0.192, 0.709$, and 0.510) and C4 ($p = 0.348, 0.055$, and 0.923) during three phases, before-FV, during-FV, and after-FV, was normally distributed. Two-way repeated-measures ANOVA revealed that the interaction electrode × condition ($F(2, 38) = 0.323$; $p = 0.726$) and the main factor electrode ($F(1, 19) = 2.135$; $p = 0.160$) were not significant, while the main factor condition ($F(2, 38) = 4.818$; $p = 0.014$) was significant. The paired-sample t-test for the relative power at C3 and C4 showed a significant increase after FV compared to before-FV (one tailed: $p = 0.033$ and 0.017). After the Bonferroni correction, the relative power of C4 after FV showed a significant increase compared to before-FV ($p = 0.034$), as shown in Figure 2.

3.2. Pearson's Correlation Analysis. The values of MRPD at C3 and C4 in the alpha and beta bands are shown in Figure 3. A significant negative correlation was found between MRPD at C4 in the alpha band and one in the beta band during FV ($p = 0.03$, Pearson's $r = -0.43$), as well as after FV ($p = 0.043$, Pearson's $r = -0.39$) (Figure 3). No significant correlation was found between MRPD at C3.

3.3. Functional Connectivity Analysis. After FDR correction tests, the connection strength of Cz-CP6, Cz-FC1, Cz-C3, C4-FC6, and FC6-CP2 in the central region showed a significant increase in the alpha band during FV, which is shown in Figure 4. The p values of connection strength of five channel pairs were 0.0093, 0.0259, 0.0261, 0.0047, and 0.0351, respectively.

4. Discussion

In order to investigate the effect of FV applied over upper limb muscles on sensorimotor cortex during FV and after FV, the experiment was conducted in which FV was delivered to the muscle belly of biceps brachii in the left arm and EEG was monitored in three phases, before FV, during

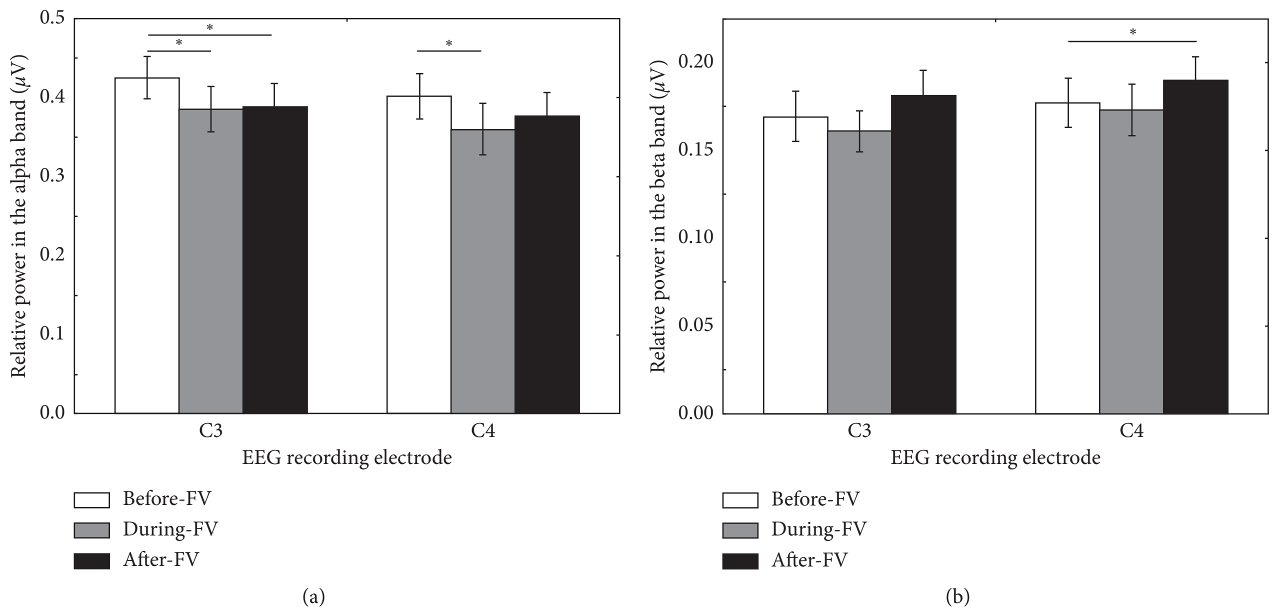

Figure 2: Relative power of the alpha band (a) and beta band (b) at C3 and C4 before FV (white), during FV (grey), and after FV (black). Note: mean values of relative power with SEM are present in charts; asterisks indicate significant differences ($p < 0.05$).

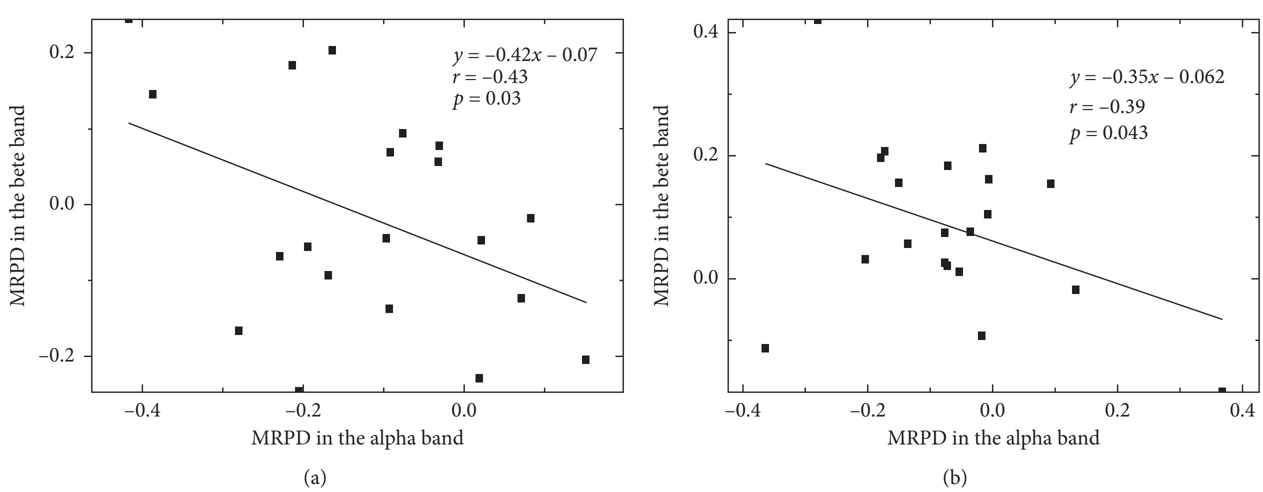

Figure 3: Pearson's correlation between alpha MRPD and beta MRPD during FV (a) and after FV (b) at C4. Solid squares indicate each subject's MRPD.

FV, and after FV. The results showed that FV on upper limb muscles could activate bilateral S1 and strengthen connection strength of the central region, including Cz-FC1, Cz-C3, Cz-CP6, C4-FC6, and FC6-CP2. The effect could not be maintained two minutes after FV. We also find that the changes of relative power at C4 in the alpha band have a negative correlation with the ones in the beta band during FV and after FV.

4.1. Before FV and during FV. In the present study, the results show that the application of FV over the muscle belly of biceps brachii in the left arm can activate contralateral S1. The "mu" rhythms originate mainly in the somatosensory postcentral gyrus [19, 20]. Moreover, the previous studies found that desynchronized power in the alpha band had a positive correlation with the activation of S1 [20, 23–25]. The present result was in line with the previous studies showing that vibrotactile at the palm or finger could activate contralateral S1 using fMRI [14, 16, 18]. It also meant that FV, which was similar to motor preparation, motor execution, motor imagery, and somatosensory stimuli, induced alpha-ERD pattern [22, 37, 38]. There was a consensus that muscle spindle and cutaneous mechanoreceptors, like Merkel afferents, Meissner afferents, and Pacinian afferents, responded to FV at the frequency of 75 Hz applied over muscle belly [39]. Based on this, it could be inferred that the activation of S1 could result from two pathways. One way is that the proprioceptive information from muscle spindle travels along the upper body proprioceptive pathway, which

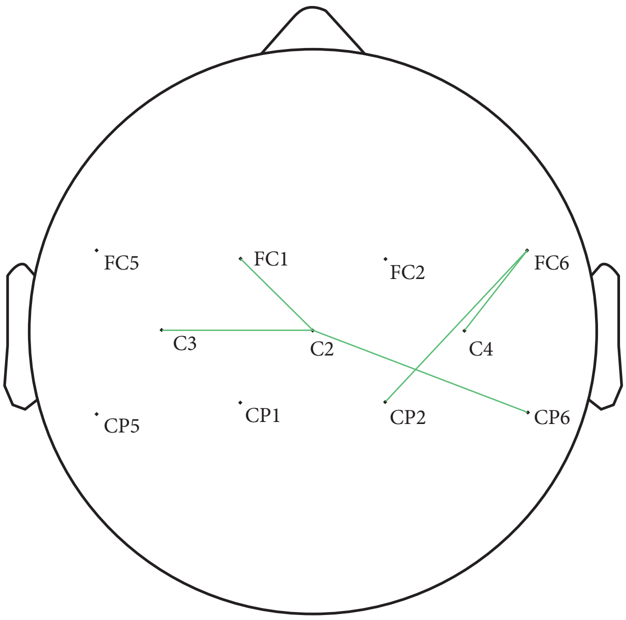

Figure 4: Connection strength of different channel pairs with significant differences during FV in the alpha band after FDR correction.

decussates in the caudal medulla through the posterior column-medial lemniscus pathway, finally to reach S1 through the ventral posterior lateral nucleus of the thalamus. The other pathway is that this cutaneous mechanoreceptor information conveys by a separate set of first-order neurons located in the trigeminal ganglion, then ascends to the ventral posterior medial nucleus of the thalamus through the neurons given off by the trigeminal brainstem nuclei, and finally reaches S1 [39]. Besides, the present result shows the occurrence of the activation of ipsilateral S1 following FV, which could originate from the input of about 10% uncrossed corticospinal tracts [40]. The activation of ipsilateral S1 following FV is also found in several studies [14, 15].

In the present study, the connection strength of Cz-FC1, Cz-C3, Cz-CP6, C4-FC6, and FC6-CP2 can be strengthened following FV. Some studies showed that C3 and C4 could project close to postcentral gyrus whilst Cz and FC1 could project close to precentral gyrus [35, 41, 42]. It seemed that the connection strength between ipsilateral postcentral gyrus and precentral gyrus is strengthened, which is similar to earlier findings indicating that functional connectivity of the ipsilateral sensorimotor area during real movements was strengthened [43].

4.2. Before FV and after FV. After FV, the present study shows that the relative power at C4 in the beta band has a statistically significant increase, which indicates the rebound of beta power after FV. It has been generally accepted that beta rebound coincided with reduced excitability of motor cortex neurons, which is similar to the phenomenon after active movement, passive movement, motor imagery, and somatosensory stimulation [21, 44–46]. Based on "functional inhibition" hypothesis, a desynchronized alpha band following the occurrence of a synchronized power in the beta band could reflect a mechanism of functional inhibition of the motor cortex by somatosensory processing [47]. It could be inferred that the activation of somatosensory cortex induced by FV could inhibit the excitability of motor cortex after FV. In the present study, the occurrence of alpha MRPD and beta MRPD at C4 shows a significant negative correlation between during-FV and after-FV. It is in line with the previous result showing that a stronger mu rhythm ERD appeared with an enhanced beta ERS with foot movement [22]. Besides, no significant reduction of relative power at C4 in the alpha band showed that the excitability of S1 was not maintained about two minutes after FV.

The differences between our findings and the current literature are that M1 is not activated and the duration of the excitability of sensorimotor areas induced by FV is shorter in this study. In the previous fMRI studies, FV applied at the hand palm or finger could activate M1 [14, 15, 18]. On the one hand, the number of muscle spindles per gram of muscle tissue at other sites of limb muscles was lower than at the hand palm (130/g) [14, 48]. The proprioceptive input is too weak to induce the activation of M1. One the other hand, it might be ascribed to the difference in the amplitude of FV. One study showed that vibration stimulus with low amplitude (0.4 mm) activated sensory and motor cortex more strongly than high amplitude (1.6 mm) [17]. In addition, the duration of effect could be related to the lasting time of FV. There were several studies using TMS showing that the excitability of sensorimotor cortex was not enhanced shortly after short-lasting FV [49–51], whilst the excitability of sensorimotor cortex lasted for longer time after long-lasting vibration stimulation [52]. Recently, one study also showed that FV could increase the excitability of S1-M1 immediately after FV, but the time of FV lasted for about thirty minutes [33].

Notably, our results show that FV could activate S1 and strengthen the functional connectivity of the sensorimotor system. The activation of S1 could play an important role in the recovery of motor function in patients with neurological diseases. On the one hand, somatosensory input from FV to the motor cortex, via corticocortical connections with S1, plays a critical role in motor relearning after hemiparetic stroke [53, 54]. On the other hand, FV, as one of the most effective modulators of cortical structure and function, could modify synaptic efficacy and transmission and as a consequence causes a cortical reorganization of the somatosensory representational maps. The reorganization of function and structure could contribute to the recovery of limb motor function. In the present study, the results using EEG are similar to ones using fMRI. It could be an appropriate way for EEG to further investigate the underlying neurophysiological mechanisms of FV on rehabilitation of motor function.

One important limitation of this study is that this is a pilot study, but not a randomized controlled trial. It cannot be precluded that part of the effects occurred could be due to the experimental procedure and not due to vibration stimulation. Nevertheless, our findings indicate that FV could activate the sensorimotor cortex and strengthen the connection strength between central regions by a comparison of before-FV with during-FV. It can be feasible to explore the effect of FV on sensorimotor cortex using EEG for later use on clinical research. In a future clinical experiment, a randomized controlled trial will be designed to explore the mechanism of FV in motor rehabilitation using EEG.

5. Conclusion

Our study shows that FV on upper limb muscles could activate the activity of primary somatosensory cortex and strengthen connection strength of the central region. Based on our present results, we will investigate the effect of FV on the activation of sensorimotor cortex for stroke patients, to further explore the underlying neurophysiological mechanisms of FV on rehabilitation of motor function in the clinical experiment.

Data Availability

The EEG data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no financial or personal conflicts of interest.

Acknowledgments

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Clinical Study

Effects of a Game-Based Virtual Reality Video Capture Training Program Plus Occupational Therapy on Manual Dexterity in Patients with Multiple Sclerosis: A Randomized Controlled Trial

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Neurorehabilitation is a fundamental aspect in the treatment approach for multiple sclerosis (MS), in which new technologies have gained popularity, especially the use of virtual reality (VR). The aim of this paper is to analyze an occupational therapy (OT) intervention compared with OT + VR (OT + VR) on the manual dexterity of patients with MS. 26 MS subjects were initially recruited from an MS patient association and randomized into two groups. The OT group received 20 conventional OT sessions distributed in two sessions per week. The OT + VR group received 20 sessions of VR interventions, twice weekly and lasting 30 minutes, consisting of VR games accessed via the online web page motiongamingconsole.com, in addition to the conventional OT sessions. Pre- and postintervention assessments were based on the Purdue Pegboard Test, the Jebsen-Taylor Hand Function Test, and the Grooved Pegboard Test. Clinical improvements were found regarding the precision of movements, the execution times, and the efficiency of certain functional tasks in the Purdue Pegboard Test and Jebsen-Taylor Hand Function Test tests in the OT + VR group. Although significant differences were not found in the manual dexterity between the OT and OT + VR groups, improvements were found regarding the precision and effectiveness of certain functional tasks.

1. Introduction

Multiple sclerosis (MS) is a chronic inflammatory demyelinating illness of the central nervous system (CNS) of unknown etiology, currently representing the most common neurological illness causing disability among young adults in Europe and North America [1]. Common symptoms include fatigue, visual disorders, problems affecting balance and coordination, sensitivity disorders, spasticity, cognitive and emotional disorders, speech disorders, problems affecting the bladder and intestines, and sexual-related dysfunction [2].

Different disease courses exist for MS, according to the appearance of symptoms, characterized by relapses or flare-ups, which vary from one episode to the other, according to the affected CNS region. The different types of MS include relapsing-remitting MS, primary progressive MS, secondary-progressive MS, and progressive-recurrent MS

[3]. Relapsing-remitting MS is the most common form of MS, whereas progressive-recurrent MS is the least common type of illness.

The treatment of MS commonly features both pharmacological and rehabilitation treatments. Rehabilitation programs can increase the effectiveness of pharmacological treatment by providing symptomatic treatment of MS to improve the quality of life and functional independence of affected individuals. The main therapeutic demands are the alterations of postural control and the performance of activities of daily living (ADLs) [4–6]. Occupational therapy (OT) evaluates the capacities and physical, psychological, sensory and social problems of individuals with MS, to support their independence in daily living and/or to facilitate adaptation to their disability [7].

At times, rehabilitation treatments for patients with MS can be very lengthy and systematic, leading to loss of motivation and compliance. As a result, in recent years, new intervention strategies have been introduced, such as virtual reality (VR), thanks to VR motion capture technology, without requiring a device or controller. These novel approaches enhance patient motivation by enabling the practice of functional tasks in virtual surroundings, providing patient feedback concerning results, all of which is based on the repetition of ADLs. Thus, rehabilitation professionals have expanded the care of patients with MS, by including this technology as a complement to rehabilitation programs, achieving a higher treatment intensity at a sustainable cost [8]. However, few studies exist on the effects that VR has on the manual dexterity of patients with MS [9–11]. Thus, the aim of this study was to analyze the effects of an OT intervention combined with VR on manual skills, compared with conventional OT approaches in people with MS.

2. Methods

2.1. Study Design. We conducted a single-blinded randomized controlled trial (RCT). Nonprobabilistic sampling of consecutive cases was used. The sample was divided into a control group (OT) who received conventional OT treatment and an experimental group (OT + VR) who received VR treatment in addition to their conventional treatment sessions. All interventions were performed at the Mostoleña Association of Multiple Sclerosis (AMDEM) in Madrid (Spain).

The study inclusion criteria were as follows: a diagnosis of MS according to the McDonald criteria [2] with over two years evolution; a score of between 3.5 (moderate incapacity, although totally ambulant, self-sufficient, and active during 12 hours/day) and 6 (requires constant help, either unilaterally or intermittently with a walking stick or crutches, in order to walk approximately 100 meters with, or without, a rest) on the Kurtzke Expanded Disability Status Scale (EDSS); with stable medical treatment during at least the six months prior to the intervention; muscle tone in the upper limbs not greater than two points on the modified Ashworth Scale (moderate hypertonia, increased muscle tone through most of the range of movement, but affected part easily moved); as well as a score of four points or less in the "Pyramidal Function" section of the EDSS functional scale; absence of cognitive decline; with the ability to understand instructions and obtaining a score of 24 or more in the Mini-Mental Test; and a score of two points or less in the "Mental Functions" section of the EDSS.

The exclusion criteria were a diagnosis of another neurological illness or musculoskeletal disorder different to MS; the diagnosis of a cardiovascular, respiratory, or metabolic illness or other conditions which may interfere with the study; suffering a flare-up or hospitalization in the last three months prior to commencement of the assessment protocol or during the process of the therapeutic intervention; receiving a cycle of steroids, either intravenously or oral, six months prior to the commencement of the assessment protocol and within the study period of intervention; receiving treatment with botulinum toxin in the six months prior to the beginning of the study; or the presence of visual disorders noncorrected by optical devices.

All participating subjects voluntarily signed an informed consent form. The present study was approved by the Research Ethics Committee of the Rey Juan Carlos University (Ref 26/12).

2.2. Participants. Twenty-six subjects with relapsing-remitting MS were initially recruited and randomized into two groups by tossing a coin. Thereafter, 10 subjects could not complete the study due to relapses or noncompliance with the treatment program. Finally, the control group (OT) comprised eight participants ($n = 8$), and the experimental group (OT + VR) also comprised eight participants ($n = 8$) (Figure 1).

2.3. Intervention. Conventional OT treatment consisted of 20 sessions during which subjects performed activities for training manipulative and functional dexterity of the upper limb aimed at ADLs. These were distributed in two OT sessions per week, each lasting 30 minutes.

The intervention applied to the experimental group consisted of 20 sessions of conventional OT distributed in two sessions per week, each lasting 30 minutes. Additionally, they received 20 treatment sessions lasting 20 minutes, twice weekly of VR via the online and free website motiongamingconsole.com, during which they performed exercises with video capture of the upper limb movements via the performance of functional and manual dexterity activities based on the following games: Flip Out, Air Hockey, Particles, DunkIt, Counting Fish, and Robo Maro. There were not used a hand controller or armbands. All exercises were designed to promote specific practice of movements in the shoulder, elbow, wrist, and/or hand through games displayed on a computer. OT + VR sessions included leisure activities such as playing cards, hitting a hockey puck, moving particles through a virtual scenario avoiding colliding with other elements, fishing, and playing "Jenga". Patients were instructed to remain in a sitting position and use both upper limbs in these activities. All tasks present a timer as a visual feedback.

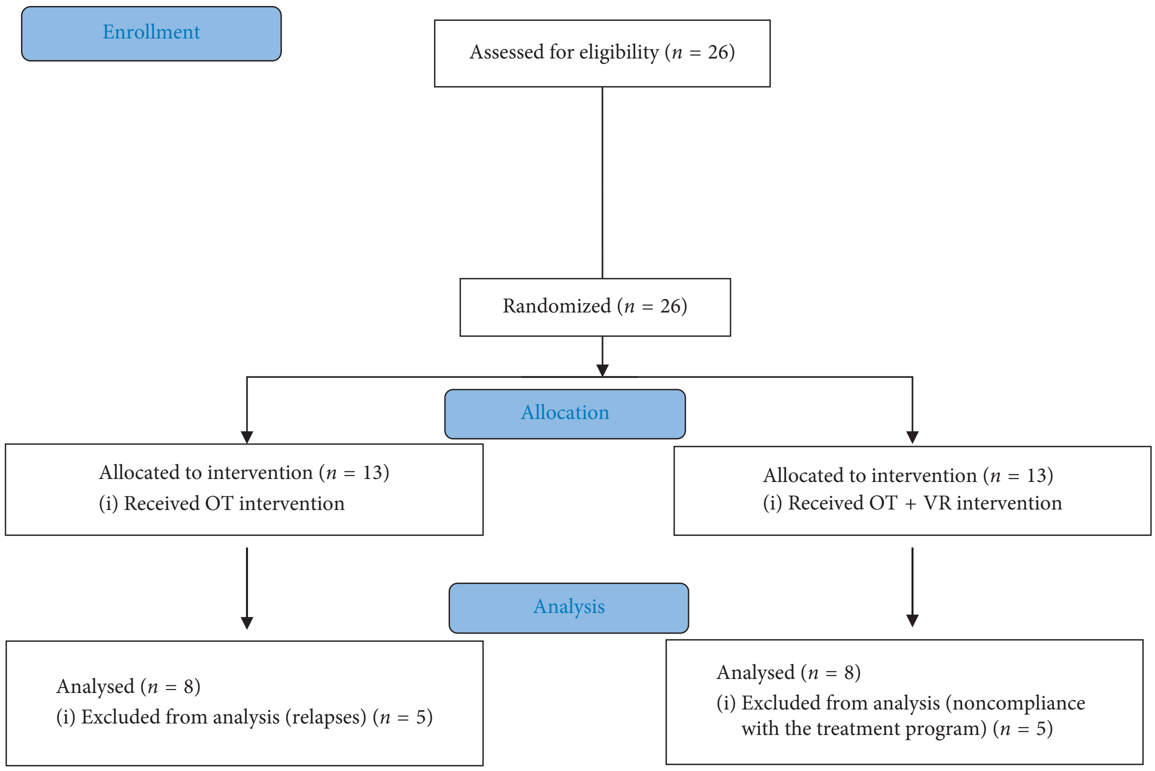

Figure 1: Flowchart diagram.

All OT and OT + VR interventions were performed by two occupational therapists, one for each modality, experts on MS neurorehabilitation. All interventions considered the level of fatigue experimented by each patient based on a progressive increase in treatment times according to the same.

2.4. Outcome Measures. All assessments were performed by physical therapists trained in the use of the measures and blinded to the intervention received by the subjects. The following outcome measures were used in both groups, both at the beginning and at the end of the intervention.

The *Purdue Pegboard Test* (PPT) [12, 13] was used for the assessment of fine manual dexterity, gross dexterity, and coordination. This test evaluates the speed and motor dexterity of each hand and the manual dexterity using both hands at the same time. The PPT features a board with two columns with 25 holes each and a specific number of pins, washers, and collars placed in four containers across the top of the board. The test consists of inserting as many pins as possible in three distinct phases, with a time limit of 30 seconds for each part. First, the test is performed with the dominant hand, then with the nondominant hand, and then with both hands at the same time. The number of pins inserted is recorded.

The *Jebsen-Taylor Hand Function Test* (JTT) [14] was used to determine the hand's functional capacity. This test is timed and divided in seven parts. The seven subtests are writing, page turning, picking up small common objects, simulated feeding, stacking checkers, moving large light objects, and moving large heavy objects.

All the subtests are performed with the nondominant hand first, followed by the dominant hand. The time the subject takes to perform each subtest is recorded.

The *Grooved Pegboard Test* (GPT) [15] is a test that evaluates manipulative dexterity. This test is performed with the dominant hand and consists of inserting pegs in the slots of a board which are placed at different angles. The score is the time in seconds required for inserting all the pegs [16].

All the data were introduced into the SPSS v.17.0 statistical package. A descriptive analysis of the quantitative variables was performed using measures of central tendency and dispersion measures: mean ± standard deviation (SD) and range. The pre-post comparison of each group and the comparisons between the control and experimental group were performed via the nonparametric Wilcoxon and Mann–Whitney U tests, respectively, as the data did not follow a normal distribution. The level of statistical significance was set at $p < 0.05$.

3. Results

16 patients (8 males and 8 females) successfully completed the study. The mean age of subjects was 46.44 years (SD 9.09). Concretely, in the control group (4 males and 4 females), the mean age was 46.13 years (SD 9.49), and in the experimental group (4 males and 4 females), it was 46.75 years (SD 9.31). The age range in the OT group was 32–61 years, and in the OT + VR group, it was 33–62 years. For the totality of the sample, the dominant hand was the

right in 62.5% of subjects. Regarding change in dominance (patients who had to change their dominance to the other hand due to impairment), in 25%, the dominant hand prior to the appearance of MS was the left, and for 75% of the sample, it was the right.

Participants from both study groups attended 100% of the proposed sessions in both protocols. No adverse effects were registered.

3.1. Intragroup Pre-Post Comparison. Regarding the pre-post intervention data for the PPT, in the case of the control group (Table 1), a greater number of total pins were registered in the postintervention assessment, although statistically significant data were not obtained ($p > 0.05$). Regarding the differences in the JTT in the control group (Table 2), statistically significant differences were found regarding "Writing with the nondominant hand" ($p = 0.018$) and "Picking up small common objects with the dominant hand" ($p = 0.012$). Besides, improvements were observed regarding the execution time of tasks, although these values did not reach the level of statistical significance (Table 2). On the contrary, in the GPT, the control group increased the final mean scores in the number of correctly placed pieces using the dominant and nondominant hand, as well as the execution time and the number of pieces picked up and placed with the dominant hand, although these values did not reach statistical significance (Table 3).

Table 1 shows the PPT pre-post intervention scores for the experimental group. A slight decrease in the number of inserted pins was observed; however, the results do not appear statistically significant. Table 2 displays the pre-post intervention data for the JTT test obtained by the experimental group. Statistically significant changes were found in the tasks "Picking up small common objects" with the nondominant hand ($p = 0.036$) and the dominant hand ($p = 0.017$). A tendency towards statistical significance was observed for the task "Page turning" with the dominant hand. Table 3 features the pre-post intervention data for the GPT test in the experimental group. Statistically significant differences were found in the item "number of correctly placed pegs" with the nondominant hand ($p = 0.078$). Furthermore, improvements were found in the times of the nondominant hand at the end of the intervention; however, these results were not significant ($p > 0.05$). Also, there was an increase in the correct placement of pegs and in the number of pegs fallen and placed with both hands, without this being statistically significant.

3.2. Intergroup Pre-Post Intervention Comparisons. The intergroup comparisons for the PPT revealed no statistically significant differences ($p > 0.05$) (Table 1). Table 2 displays the intergroup comparisons for the JTT. No statistically significant differences were found for any of the variables ($p > 0.05$) (Table 2). The intergroup comparison of the GPT also failed to reveal statistically significant results ($p > 0.05$) (Table 3).

4. Discussion

Our findings reveal that significant differences do not exist in the treatment of manual dexterity in subjects performing the OT + VR intervention when compared to those receiving conventional OT treatment. However, statistically significant differences were found in items such as "Picking up small common objects" using the nondominant hand and the dominant hand, with a tendency towards statistical significance in the case of "Number of correctly placed pegs" in the OT + VR group. Furthermore, several variables related to effectiveness and motor dexterity also showed a tendency towards statistical significance in both groups.

Regarding the conventional OT intervention, statistically significant differences were observed in the JTT test for the following items: "Writing" in the nondominant hand and "Picking up small objects" with the dominant hand. To our knowledge, this study is the first to evaluate manual dexterity in a population of MS, using the JTT. The results obtained may be due to the therapeutic approach of OT in patients with MS, based on the performance of functional activities with the upper limb, as well as training the change in hand dominance to enable a greater participation in ADLs [3].

Concerning the combined OT + VR interventions, the number of pins inserted between the initial and final assessments was maintained in the PPT test. Gallus et al. [17] identified the PPT as a valid measure for evaluating fine motricity and gross coordination in people with MS. In the JTT test, significant changes were observed in the tests "Picking up small common objects" with the dominant and nondominant hand, as well as a tendency towards statistical significance in the "Page turning" item. In the GPT test, improvements that were close to statistical significance were found in the number of correctly placed items. Possibly, the limitation of the sample size may have influenced these results. In the scientific literature, we were unable to find studies related with the assessment of motor dexterity via the application of the JTT and the GPT in people with MS. However, Lozano et al. [11] used the JTT in people with brain damage, finding a clinical and significant improvement in the performance of daily functional tasks such as "Page turning" and "Picking up small common objects", using low-cost virtual reality surroundings with video capture of movement using the Kinect system. The results of the cited study coincide with our findings based on a free online games platform used in which the upper limb movements of patients with MS were registered during the performance of functional tasks. Given the context of our study, taking place at a patient association, the online platform may be interesting for situations in which there may be insufficient economic resources to enable the acquisition of new equipment. On the contrary, Merians et al. [18] also used the JTT to evaluate the fine motor dexterity of patients with brain damage as a measure of results after the VR intervention, finding clinical improvements in the speed and precision of fine movements, and in some subjects, a post-intervention generalization of learning to ADLs. These data are in line with our findings, in which clinical improvements existed, without achieving statistical

Table 1: Differences pre-post intervention in Purdue Pegboard Test (PPT) in the control group and experimental group.

PPT	OT Pretreatment Mean ± SD	OT Posttreatment Mean ± SD	p	OT + VR Pretreatment Mean ± SD	OT + VR Posttreatment Mean ± SD	p	p
DH	6.25 ± 3.65	7.50 ± 4.07	0.319	7.50 ± 4.07	7.37 ± 3.37	0.792	0.832
NDH	5.25 ± 3.57	4.00 ± 2.56	0.263	4.00 ± 2.56	4.25 ± 2.25	0.48	0.707
Bilateral	3.54 ± 2.11	3.62 ± 1.99	1	3.62 ± 1.99	3.37 ± 2.06	0.577	0.665
Assemble	2.57 ± 1.27	3.00 ± 1.63	0.518	3.00 ± 1.63	2.50 ± 2.22	0.785	0.448
Total number of pins	17.61	18.12	0.898	18.12	17.49	0.602	

DH: dominant hand; NDH: nondominant hand. Time in seconds.

Table 2: Differences pre-post intervention in Jebsen-Taylor Hand Function Test (JTT) in the control group and experimental group.

JTT	OT Pretreatment Mean ± SD	OT Posttreatment Mean ± SD	p	OT + VR Pretreatment Mean ± SD	OT + VR Posttreatment Mean ± SD	p	p
Writing NDH* (time)	93.25 ± 73.68	62.92 ± 42.92	**0.018**	62.92 ± 42.92	50.68 ± 39.57	0.866	0.655
Page turning NDH (time)	7.98 ± 3.75	6.34 ± 2.30	0.889	7.80 ± 4.01	8.87 ± 3.25	0.208	0.248
Picking up small common objects NDH (time)	13.22 ± 6.09	10.62 ± 4.15	0.779	16.24 ± 10.08	16.73 ± 10.19	0.327	0.6
Simulated feeding NDH (time)	32.70 ± 32.66	17.75 ± 8.50	0.779	26.79 ± 19.09	26.34 ± 19.87	0.779	0.793
Stacking checkers NDH (time)	10.68 ± 10.88	6.76 ± 5.78	0.674	13.90 ± 17.87	22.91 ± 35.00	0.208	0.294
Moving large light objects NDH‡ (time)	8.15 ± 5.03	5.78 ± 2.05	0.08	6.98 ± 3.38	8.89 ± 5.71	**0.036**	0.345
Moving large heavy objects NDH (time)	6.84 ± 2.67	5.39 ± 1.13	0.779	7.06 ± 2.20	7.64 ± 2.32	0.327	0.4
Writing DH (time)	39.99 ± 21.68	38.40 ± 24.66	0.674	38.40 ± 24.66	37.21 ± 23.44	0.674	0.834
Page turning DH (time)	8.00 ± 2.75	6.34 ± 2.30	0.093	6.34 ± 2.30	8.14 ± 3.16	0.069	0.208
Picking up small common objects DH (time)	12.26 ± 2.14	10.62 ± 4.15	0.208	10.62 ± 4.15	13.02 ± 5.25	0.263	0.529
Simulated feeding DH (time)	16.39 ± 4.84	17.75 ± 8.50	0.484	17.75 ± 8.50	19.09 ± 7.33	1	0.529
Stacking checkers DH (time)	7.84 ± 4.47	6.76 ± 5.78	0.401	6.76 ± 5.78	8.15 ± 3.76	0.123	0.208
Moving large light objects DH*‡ (time)	6.12 ± 1.66	5.78 ± 2.05	**0.012**	5.78 ± 2.05	6.45 ± 1.87	**0.017**	0.294
Moving large heavy objects DH (time)	6.11 ± 1.30	5.39 ± 1.13	0.208	5.39 ± 1.13	7.01 ± 1.93	0.263	0.093

*The difference between pretreatment and posttreatment in the control group is statistically significant. ‡The difference between pretreatment and posttreatment in the experimental group is statistically significant. DH: dominant hand; NDH: nondominant hand. Time in seconds.

Table 3: Differences pre-post intervention in Grooved Pegboard Test (GPT) in the control group and experimental group.

GPT	OT Pretreatment Mean ± SD	OT Posttreatment Mean ± SD	p	OT + VR Pretreatment Mean ± SD	OT + VR Posttreatment Mean ± SD	p	p
Time NDH	339.12 ± 277.94	340.25 ± 276.80	0.686	340.25 ± 276.80	336.18 ± 277.73	0.715	0.955
Number of fallen pegs (and collected to replace) NDH	3.71 ± 2.98	4.85 ± 3.62	0.245	4.85 ± 3.62	5.37 ± 4.56	0.336	0.861
Number of correctly placed pegs NDH	20.14 ± 8.47	21.14 ± 4.63	0.465	15.37 ± 9.67	21.14 ± 4.63	0.078	0.239
Time DH	203.52 ± 83.98	185.40 ± 58.03	0.499	185.40 ± 58.03	205.58 ± 74.64	0.237	0.674
Number of fallen pegs (and collected to replace) NDH	3.37 ± 3.20	2.50 ± 1.92	0.246	2.50 ± 1.92	3.25 ± 3.41	0.226	0.915
Number of correctly placed pegs NDH	23.75 ± 3.53	24.00 ± 2.82	0.317	24.00 ± 2.82	22.75 ± 4.30	0.18	0.538

DH: dominant hand; NDH: nondominant hand. Time in seconds.

significance, possibly due to the reduced sample size after the losses experienced during the study. It is well-known that the performance of functional tasks, repeated over time and with certain variability, can lead to a relearning of skills. This is an aspect reinforced by VR by offering feedback of results in real time [17, 19, 20].

We found no differences between the application of OT and OT + VR on the manual dexterity of MS patients with a moderate level of impairment in the PPT, JTT, and GPT tests. However, clinical improvements were found after the OT + VR intervention, with improved precision of the upper limb movements, faster performance. and a greater efficiency in the performance of certain functional tasks. Previous qualitative studies [21] on the subjective experience of using VR systems, based on video capture of movement with Kinect as a therapeutic tool in patients with MS, have identified improvements in patient's self-efficacy for management of the illness, social support, expectations, and training offered, as well improvements in the behavior and perception of the person's own identity, and a positive association between the physical activities performed with VR and the real environment. These results have been confirmed in similar studies

[22, 23] highlighting the potential usefulness of these low-cost systems as a complement to conventional approaches from the perspective of MS patients.

As previously mentioned, we were unable to find previous scientific studies associating improvements in manipulative dexterity using OT treatment approaches combined with VR in patients with MS. Shin et al. [24] found clinical improvements in manipulative dexterity after a VR intervention in people with brain injury, measured using the PPT and JTT. Significant differences were however not found in the cited study among the group receiving conventional OT, leading the authors to conclude that the combination of conventional OT with VR may improve global upper limb movements. Our results contrast partially with those by Shin et al. as an improvement seems to exist in our OT group, as well as the OT + VR group, although significant differences were not found between both study groups. This suggests that both approaches could be valid, and, fundamentally, complementary. Findings by our research group [17, 19, 20], as well as those reported by other authors [25], have shown improvements in postural control, optimization of the processing of the sensory information, and integration of the systems necessary for maintaining balance and postural control in people with MS via the use of low-cost VR systems. Therefore, future research lines could employ whole body exercise programs with subjects in different lying positions to enhance a potential generalization of learnings to other contexts and situations in which the patient may require manual dexterity.

This study has several methodological limitations. We used a small sample size, which hampers the detection of statistically significant differences, although these may well exist. Furthermore, a high number of losses occurred due to the fluctuating nature of the illness. Also, the outcome measures used had not been previously employed in the clinical context of MS; therefore, despite their good psychometric properties, this has hampered the discussion of results regarding the manipulative dexterity in patients with MS. Lastly, future studies should consider assessments with midterm follow-up.

5. Conclusions

Our results show that there are no significant differences regarding manual dexterity when comparing a conventional OT intervention with an OT + VR intervention in patients with MS with a moderate level of severity. However, patients receiving an OT + VR intervention showed clinical improvements in the precision of certain upper limb movements, faster execution times for certain tests, and greater effectiveness during certain functional tasks. Therefore, VR using video capture of upper limb movements could be a complementary intervention to OT in the treatment of manual dexterity in patients with MS.

Data Availability

All data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

CNWP, CGC, and LAT performed treatments; MIJT was responsible for the methodology; ABF, RCC, and RMOG were involved in writing and original draft preparation; RCC was involved in writing, editing, and reviewing of the manuscript.

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Research Article

Integrated System for Monitoring Muscular States during Elbow Flexor Resistance Training in Bedridden Patients

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To improve or maintain the physical function of bedridden patients, appropriate and effective exercises are required during the patient's bed rest. Resistance training (RT) is an effective exercise for improving the physical function of bedridden patients, and the improvement of the physical function is caused by mechanical stimuli associated with RT. Currently, the measured mechanical stimuli are external variables which represent the synthetic effect of multiple muscles and body movements. Important features of stimuli experienced by muscles are of crucial importance in explaining muscular strength and power adaptation. This study describes an integrated system for assessing muscular states during elbow flexor resistance training in bedridden patients, and some experiments were carried out to test and evaluate this system. The integrated system incorporates an elbow joint angle estimation model (EJAEM), a musculoskeletal model (MSM), and a muscle-tendon model. The EJAEM enables real-time interaction between patient and MSM. The MSM is a three-dimensional model of the upper extremity, including major muscles that make up the elbow flexor and extensor, and was built based on public data. One set of concentric and eccentric contraction was performed by a healthy subject, and the results of the calculations were analyzed to show important features of mechanical stimuli experienced by muscles during the training. The integrated system provides a considerable method to monitor the body-level and muscle-level mechanical stimuli during elbow flexor resistance training in bedridden patients.

1. Introduction

Patients are confined to bed as a consequence of illness, aging, and major surgery. Data from the Ministry of Health, Labour and Welfare show that there are approximately 1.7 million bedridden older adults in 2010 in Japan and this number will increases to 2.3 million in 2025 [1]. The prolonged bedridden behavior of patients will exacerbate skeletal muscle wasting and consequently results in the decline of physical function [2, 3]. The decreased physical function increases the patient's dependence on bed rest, which in turn exacerbates the patient's condition. In order to reverse this exacerbation, appropriate and effective exercises are required during the patient's bed rest [4].

Many studies provided evidence that the resistance training (RT) is an effective method for improving physical function of the bedridden patient [5–7]. The RT refers to the exercise that causes the muscles to contract against an external resistance for the purpose to increase muscular strength and power. During RT, it is thought that the improvement of muscular strength and power is caused by mechanical stimuli, which are related to the kinematic and kinetic variables associated with RT (e.g., force, velocity, power, and work) [8].

Currently, these kinematic and kinetic variables are usually measured by using equipment such as dynamometers, linear position transducers, and force plates [9–11]. Force, displacement, and velocity are measured by using a force plate and linear position sensors. Power is calculated by sampling the system pressure or mechanically defined as the product of force and velocity. Work is calculated as the product of force and displacement. The measured force, velocity, and power are external variables which represent the synthetic effect of multiple muscles and body movements. To obtain a better appreciation of how mechanical stimuli affect strength and power adaptation, details of the training (such as details of the movement and the way how the external resistance load is applied to the body), and important characteristics of mechanical stimuli associated with the training are of crucial importance. The different ways of moving or lifting the load will have varied effects on the strength and power adaptations [8]. And only the maximum or average value of the load is not sufficient to evaluate the training effect. Moreover, aging or illness is usually accompanied by changes in the muscle's morphology and architecture (e.g., sarcopenia usually occurs with decrease in muscle mass) [12]. The appropriate volume of training for these patients is different from that of healthy people. Therefore, a scientific method is needed to quantify these differences and to see important features of mechanical stimuli during the training.

Musculoskeletal modeling is a powerful tool to research the mechanical behavior of human muscles by using the methods of mechanics [13]. This method quantifies the mechanical and physiological properties of each muscle through parametric modeling, enabling researchers to quantify muscle differences and gain insight into the states (usually refer to mechanical states such as muscle-tendon length changes, muscle fiber force, and velocity) of each muscle during the movement. In this paper, we present the concept of using musculoskeletal modeling as a methodology to estimate muscular states during RT for bedridden patients. Currently, a number of researchers use musculoskeletal modeling to study the influence of muscle intrinsic properties on sports performance of athletes such as running [14, 15] and jumping [16, 17], but few have discussed its application in RT for bedridden patients.

We searched many physical therapies recommended to people with injuries and disabilities [18] and chose the elbow flexor RT for bedridden patient. This exercise focuses on the development or maintenance of flexor strength of the upper extremity, and it is simple and applicable for many circumstances such as hospitals, rehabilitation centers, and homes. In hemodialysis patients, doctors often use it to avoid the sedentary lifestyle of patients and improve their fitness status before and after kidney transplantation [19]. Moreover, the elbow flexor RT is an important exercise in pulmonary rehabilitation [20]. Arm training will result in a significant increase in oxygen intake and exercise dyspnea, ultimately increasing arm endurance, regulating dynamic over-inflation, and reducing symptoms in patients with chronic obstructive pulmonary disease [21]. More importantly, an improvement in muscle strength will lead to an improvement in physical function of the upper limbs, such as reaching or lifting an object, and ultimately reversing the patient's dependence on bed rest [7]. For this kind of RT, this study established an integrated system to estimate the muscular states during the training. The remainder of the paper is structured as follows: Section 2 describes the design concepts of the system, details of the measurement, and analysis methods; Section 3 presents some experimental results. A brief discussion was made in Section 4.

2. Measurements and Analysis Methods

2.1. Design Concepts of the System. Figure 1 illustrates the design concepts of the system. For simplicity of the system, we only use one load cell to measure the time-varying resistance force during the training. The measured resistance force is an external variable, and its resulting power and work do not contain details of stimuli experienced by muscles. Therefore, we established an elbow joint angle estimation model (EJAEM), a musculoskeletal model (MSM), and a muscle-tendon model (MTM) to estimate muscular states during the training. The EJAEM serves as an analytical description of the experimental setup, and it enables real-time interaction between patient and MSM. The MSM is a three-dimensional model of the upper extremity, including major muscles that make up the elbow flexor and extensor and was built based on public data [22, 23]. The MSM provides the kinematics and kinetics required in optimization of muscle-tendon force (MTF) and estimation of muscular states. The MTM was established to estimate the active and passive muscle fiber force for the reason that the optimized MTF is a resultant force of active and passive muscle fiber force, and the power of active muscle fiber force is meaningful for evaluation of muscles.

Figure 2 shows the layout of the experimental setup. In the training, the patient is positioned in a bed in supine with his forearm flexing or extending to oppose resistance force produced by a custom-made TheraBand. TheraBand is connected to a load cell which is anchored to the bed by a lifting hook and is utilized to record the resistance force posed by the TheraBand. The force data are converted into a digital signal by an A/D converter and sent to a desktop using an Arduino board. A web camera is utilized to record video of the forearm movement, and the recorded video was used to calculate real elbow joint angle for the testing of the measuring system.

2.2. The Elbow Joint Angle Estimation Model. The EJAEM plays an essential role in the kinematic and kinetic analysis of forearm movement. Figure 3 illustrates the physical model used to estimate elbow joint angle, and it includes the coordinates and geometrical parameters about the training setup. In the model, L, L_1, and L_2 denote the length of TheraBand, forearm, and upper arm. S_1 and S_2 represent the x coordinate of the elbow and shoulder joint. A, B, C, and E denote the position of the shoulder, elbow, hand, and center of gravity. One end of the load cell is connected to the bed at point D by using a lifting hook, and the other end is connected to the TheraBand. θ denotes the elbow joint angle.

As we can see from the physical model, with specific H, S_1, S_2, L_1, and L_2, θ is closely related to the current length of the TheraBand L. This implies that if we know L, we can predict the elbow joint angle through some simple geometric

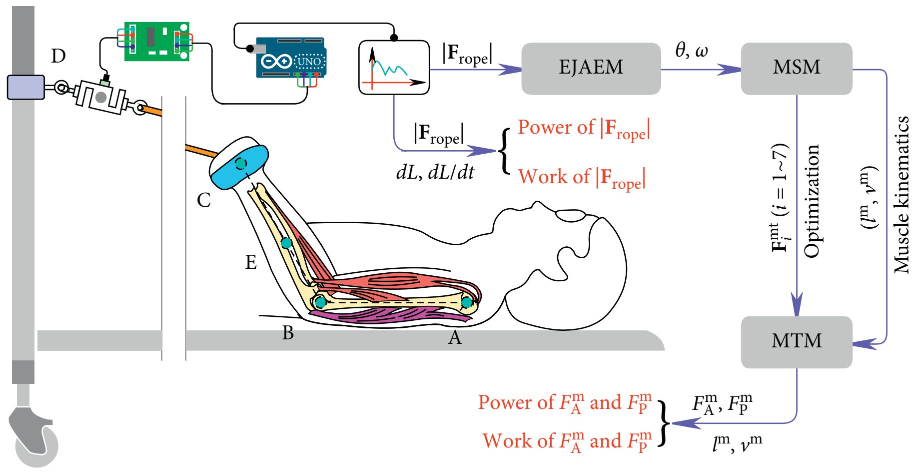

Figure 1: Design concepts of the system and data flow in estimation. θ is the elbow joint angle, and ω is the angle velocity. $|\mathbf{F}_{\text{rope}}|$ is the resistance force. dL and dL/dt are the length change and change rate of the TheraBand. $F_A{}^m$ and $F_P{}^m$ are the active muscle fiber force and passive muscle fiber force. l^m and v^m are the muscle fiber length and velocity. $\mathbf{F}_i^{mt}$ is the optimized MTF. $|\mathbf{F}_{\text{rope}}|$ represents mechanical stimuli measured at the body level, and the $F_A{}^m$, $F_P{}^m$, l^m, and v^m represent mechanical stimuli estimated at the muscle level.

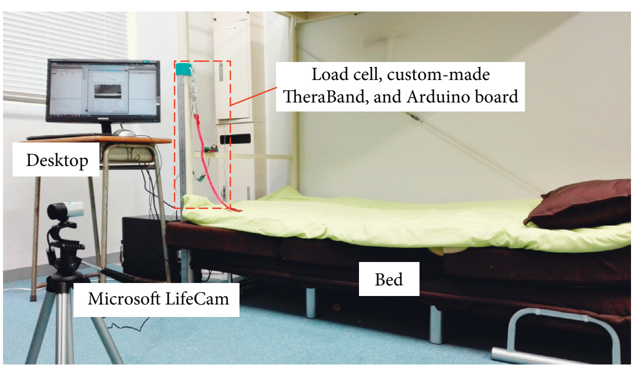

Figure 2: Layout of the experimental setup.

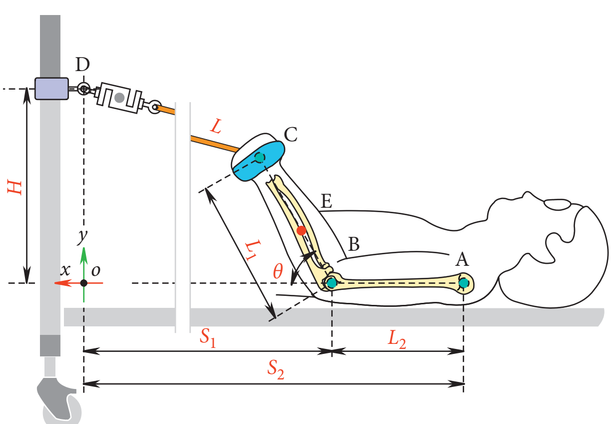

Figure 3: Physical model used to estimate the elbow joint angle and the geometric parameters and coordinates of the experimental setup. The model is a simplified two-dimensional model in the sagittal plane.

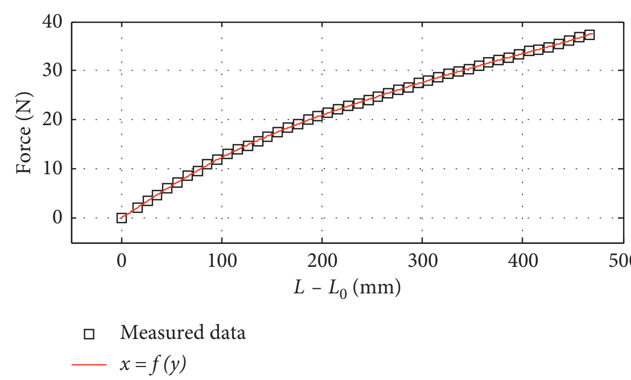

Figure 4: Load versus length-change curve of the custom-made TheraBand. L_0 is the initial length of the TheraBand.

calculation. As shown in Figure 4, we stretched the TheraBand to a series of lengths and recorded the force data to obtain its load versus length-change curve.

Figure 4 shows a strong one-to-one relationship between force and length. We use a polynomial equation to approximate the nonlinear relationship between load and length as follows:

$$L = \Psi_1\left(\left|\mathbf{F}_{\text{rope}}\right|\right), \tag{1}$$

where $\psi_1(x)$ is the polynomial equation of x and its expression is different for different custom-made TheraBands. $|\mathbf{F}_{\text{rope}}|$ is the force data recorded from the load cell and is the norm of $\mathbf{F}_{\text{rope}}$.

According to the physical model, L is a trigonometric function of θ, and its mathematical expression can be expressed as follows:

$$(H - L_1 \sin\theta)^2 + (S_1 - L_1 \cos\theta)^2 = L^2. \tag{2}$$

Because the TheraBand has an initial length L_0 and resistance force is 0 when the TheraBand length is less than L_0, the elbow joint angle estimated by EJAEM is never less than the initial angle θ_0. According to (1) and (2) and the recorded $|\mathbf{F}_{\text{rope}}|$, we eventually get θ as a function of time as follows:

$$\theta(t) = \Psi_2\left(\left|\mathbf{F}_{\text{rope}}\right|\right) = \Psi_3(t). \quad (3)$$

Furthermore, we can get the angular velocity ω as follows:

$$\omega(t) = \frac{d\theta(t)}{dt} = \frac{\Psi_3(t+dt) - \Psi_3(t)}{dt}. \quad (4)$$

2.3. Musculoskeletal Model. The elbow flexor RT incorporates concentric and eccentric movements in which flexor and extensor are dominant. According to the anatomical descriptions of the human upper limb [24], as illustrated in Figure 5, the elbow flexor and extensor primary include 7 parts of muscles. In this paper, a three-dimensional MSM of the human upper limb was established based on public data of skeletal coordinates and muscle architecture [22, 23] and by using the obstacle-set method [25] to model the muscle path. The MSM consists of 3 bones, 3 joints, and 7 parts of muscles. Table 1 shows the architectural properties of each muscle or muscle part. Additional details regarding the MSM are available in the references mentioned above [22, 23].

2.3.1. Muscle Geometry. The obstacle-set method [25] was used to model the joint configuration-depended muscle path. This method uses some regular-shaped rigid bodies, like a cylinder, to serve as obstacles fixed on and move with the skeleton to force muscles wrap on it for all joint configurations. In the obstacle-set method, the muscles were treated as mass-less, friction-less cables that follow the shortest path between the origin point and insertion point. The action line of MTF is determined by fixed or obstacle via points, origin, and insert points. Garner [25] presented the detailed descriptions of the algorithms and formulas about this method.

In the obstacle-set method mentioned above, the shortest path of muscle wrapping is computed analytically and muscle-tendon length is calculated as the sum of the straight-line segments and wrapping segments. Different from the tendon displacement method [26], we classically defined moment arm as the distance between muscle's action line and joint's axis of rotation [27]. The MSM is a detailed three-dimensional model, and the action line of muscles is usually not in the sagittal plane. As illustrated in Figure 6(b), we project their action line into the sagittal plane to calculate moment arm based on geometric calculation.

2.3.2. Optimization Process. As illustrated in Figure 6(a), the human musculoskeletal system is usually characterized by redundant muscles, and load sharing is closely related to the action line of MTF and the rotation axis. The static optimization method is usually used to solve this redundant problem. The static optimization is a computationally efficient method used in predicting redundant MTF by minimizing a cost function subject to force/torque constraints associated with a given task [28, 29]. Equilibrium equations include components in the sagittal plane, and along the rotation axis, two constraint equations were constructed for optimization. MTF is also constrained between zero and maximum MTF by an inequality constraint. The objective function is expressed as the sum of muscle stress squared. Gravity of the forearm is another contributor to the resultant moment about the elbow joint. Static optimization is formulated as follows:

$$\begin{aligned} &\text{minimize} \quad \sum_{i=1}^{n}\left(\frac{F_i^{\text{mt}}}{A_i}\right)^2, \\ &\text{subject to} \quad \begin{cases} \sum_{i=1}^{n} F_i^{\text{mt}} \cdot \mathbf{r}_\mathbf{i}' \times \mathbf{e}_\mathbf{i}' + \mathrm{M}' = [\mathbf{I}] \cdot \boldsymbol{\alpha}, \\ 0 \le F_i^{\text{mt}} \le F_{0i}^{\text{M}}, \end{cases} \end{aligned} \quad (5)$$

where F_i^{mt} is the magnitude of MTF; A_i is the physiological cross-sectional area (PCSA); $\mathbf{e}_\mathbf{i}'$ is the sagittal projection of the action line and $\mathbf{e}_\mathbf{i}'$ is the sagittal moment arm; M is the resultant joint moment of gravity, resistance force, passive muscle fiber force, and joint reaction moment and M' is its projection in the sagittal plane; $[\mathbf{I}]$ is the inertia mass matrix of the forearm; $\boldsymbol{\alpha}$ is the angular acceleration at the elbow joint (in this study, angular acceleration is relatively small and is assumed as 0); and F_{0i}^{M} is the maximum isometric muscle fiber force.

2.4. Estimation of Muscular States

2.4.1. Muscle-Tendon Model. A Hill-type muscle model was utilized to represent the intrinsic mechanical properties of human muscles. Each musculotendon actuator is represented as a 3-element muscle in series with an elastic tendon. The instantaneous length of the actuator is determined by the length of the muscle, the length of the tendon, and the pennation angle of the muscle. In this model, the pennation angle is assumed to remain constant as muscle length changes [30].

For a specific muscle i, general form of the function of the Hill-type muscle model is given by the following equation:

$$\begin{aligned} F^{\text{mt}}(t) &= F^t, \\ &= \left[F_\text{A}^{\text{m}} + F_\text{P}^{\text{m}}\right]\cos(\varphi), \\ &= \left[f_\text{A}(l) f(v) a(t) F_0^{\text{M}} + f_\text{P}(l) F_0^{\text{M}}\right]\cos(\varphi), \end{aligned} \quad (6)$$

where $F^{\text{mt}}(t) = F^t$ is the time-varying MTF; F_A^{m} and F_P^{m} are the active muscle fiber force and passive muscle fiber force; $l = l^{\text{m}}/l_0^{\text{m}}$ is the normalized muscle fiber length; $v = v^{\text{m}}/v_0^{\text{m}}$ is the normalized fiber velocity; l_0^{m} is the optimal fiber length; v_0^{m} is the maximal fiber velocity; $a(t)$ is the time-varying muscle activation; φ is the muscle pennation angle; $f_\text{A}(l)$ and $f_\text{P}(l)$ are the normalized active and passive force-length relationships; and $f(v)$ is the normalized curve of the velocity-dependent muscle fiber force. $f_\text{A}(l)$, $f_\text{P}(l)$, and $f(v)$ are the nonlinear formulas that characterize the material properties of the muscle tissue. In this model, we use the curves created by cubic spline interpolation of points defined on the Gordon Curve [31, 32]. The curves were

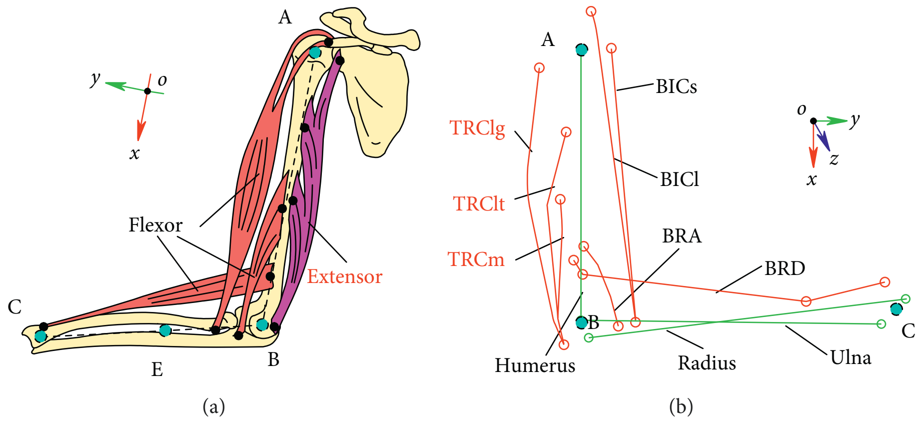

FIGURE 5: (a) Extensor and flexor of the human upper limb in the sagittal plane. (b) Three-dimensional MSM illustrates bones (green lines) and muscles (red lines) across elbow joint.

TABLE 1: Architectural properties of each musculotendon actuator of elbow extensor and flexor.

Muscles		Abbr.	PCSA (cm^2)	l_0^m (N)	v_0^m (cm/s)	lSt (cm)	F_0^M (N)	φ (deg)
Extensor	1. Triceps brachii (long)	TRClg	19.07	15.24	152.4	19.05	629.21	15.00
	2. Triceps brachii (lateral)	TRClt	38.45	6.17	61.7	19.64	1268.87	15.00
	3. Triceps brachii (medial)	TRCm	18.78	4.90	49.0	12.19	619.67	15.00
Flexor	4. Brachialis	BRA	25.88	10.28	102.8	1.75	853.90	15.00
	5. Brachioradialis	BRD	3.08	27.03	270.3	6.04	101.58	5.00
	6. Biceps brachii (long)	BICl	11.91	15.36	153.6	22.93	392.91	10.00
	7. Biceps brachii (short)	BICs	13.99	13.07	130.7	22.98	461.76	10.00

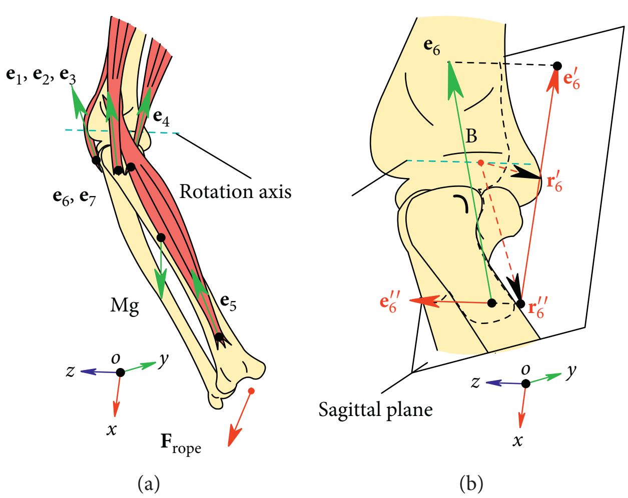

FIGURE 6: (a) Force sharing of MTF across elbow joint. $\mathbf{e}_i (i = 1-7)$ denotes the action line of MTF; (b) the action line of $\mathbf{e}_6$ was projected into sagittal plane ($\mathbf{e}_6'$) and along rotation axis ($\mathbf{e}_6''$). $\mathbf{r}_6'$ and $\mathbf{r}_6''$ are their moment arm.

normalized for force, length, and velocity. The maximum muscle fiber contraction velocity of all muscles was assumed to be $v_0^m = 10 l_0^m$ [33].

2.4.2. Estimating Muscular States. According to (6), the muscle fiber length and fiber velocity are needed in estimation of passive and active muscle fiber force. For a specific muscle, we approximate the muscle-tendon length as a function of θ:

$$l^{mt} = \Psi_4(\theta). \quad (7)$$

The muscle-tendon length includes two parts: tendon length l^t and fiber length l^m:

$$l^{mt} = l^t + l^m \cos(\varphi). \quad (8)$$

Suppose the change of muscle-tendon length is mainly the result of the change of fiber length, we have

$$\frac{dl^{mt}}{dt} = \frac{d\Psi_4(\theta)}{dt} = \Psi_5(\theta, w) = -v^m \cos(\varphi), \quad (9)$$

where v^m is the fiber velocity and $v^m > 0$ means the muscle is shortening and $v^m < 0$ means the muscle is lengthening. Figure 7 illustrates the algorithm used in the estimation of muscular states.

3. Results

3.1. Testing of the Measuring System. Contrasting experiments were carried out to test the correctness of the measuring system in estimating elbow joint angle. In the experiment, a subject was asked to perform two sets of concentric and eccentric contractions in flexor resistance training (the experiment was conducted with the subject's understanding and consent). Initial configurations of the training setup were measured using rulers and typed into the model ($S_1 = 1080$ mm, $S_2 = 1384$ mm, $L_1 = 270$ mm,

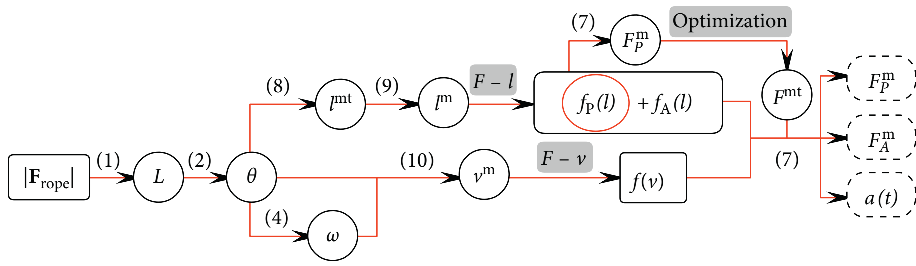

Figure 7: Block-diagram of the algorithm used to estimate muscular states.

$L_2 = 304$ mm, $L_0 = 870$ mm, and $H = 230$ mm). We recorded the video and measured the real elbow joint angle by using a protractor and compared it with that estimated in EJAEM. As we can see from the results illustrated in Figure 8, the elbow joint angle estimated in EJAEM shows good consistency with that measured from the video except when the angle is less than the initial angle θ_0. This is because when $|\mathbf{F}_{\text{rope}}|$ is zero, we set the rope length at its initial length in the program. Calibration was performed to eliminate the time delay caused by software and hardware. The good consistency between measured and estimated result demonstrates that this measuring system can correctly estimate elbow joint angle when the forearm flexes or extends in the sagittal plane.

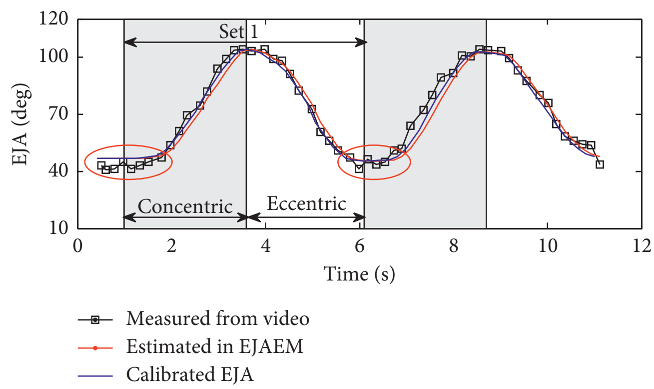

Figure 8: Comparison of elbow joint angle measured from video and that estimated in EJAEM.

3.2. Evaluation of the Musculoskeletal Model. The MSM provided by Garner [22, 23] is a detailed three-dimensional model of the human upper limb. But, the EJAEM in this paper is a simplified two-dimensional model in the sagittal plane. Therefore, we projected muscles into the sagittal plane, calculated muscle length and moment arm, and compared them with results provided by Garner [34], Lemay [35], and Garner [23] as an evaluation of the MSM. Their results were obtained by using anatomical or experimental data. As illustrated in Figures 9 and 10, muscle length and moment arm were calculated as a function of elbow joint angle with the shoulder joint at neutral position, the humerus in parallel with the y axis of the thorax, and elbow joint angle varying from 0° to 150°. We used the polynomial coefficients of muscle length and moment arm provided by Pigeon and Lemay, which were approximated by using anatomical or model data, and point data of moment arm illustrated in Garner [23]. Lemay only provided the length changes of the muscle, so we use the constant portion of muscle length provided by Pigeon [34]. The muscle length and moment arm estimated in this model demonstrate a substantial agreement with that provided in their documents, especially the moment arm compared with Garner. The data used in this model originate from the study of Garner, but we use a different method in calculating the moment arm. Garner calculated the moment arm by computing the derivative of muscle length with respect to joint angle [24]. Good coherence of muscle length and moment arm demonstrates that the established MSM captures important mechanical features of muscles across elbow joints and is adequate to serve as a generic model to analyze muscle kinematics in the case of elbow flexing or extending.

3.3. Muscular States and Mechanical Stimuli during Flexor Resistance Training. The muscular state refers to mechanical variables such as the muscle-tendon length changes and the muscle fiber velocity. Mechanical stimuli such as power and work are derivative of those mechanical variables. One set of concentric and eccentric contraction was performed by a healthy subject in flexor resistance training and data were utilized to show body-level and muscle-level stimuli in Figures 11 and 12 and in Table 2. ω, dL_{rope}, and v^{m} were the derivative of θ, rope length, and fiber length versus time, respectively; power was the product of force and velocity; work was the accumulation of the product of force and displacement over each time step; flexor and extensor power was calculated as the sum of power of flexor and extensor. Table 2 shows the work and displacement, as well as the average force of resistance force and muscles. Work is the accumulation of the product of muscle fiber force and displacement over each time step. Length change is the accumulation of small displacement over each time step, and average force is the mean value of force.

The calculated results show important characteristics about the mechanical stimuli during flexor resistance training. In concentric contraction, resistance force reaches its maximum within two seconds and the maximal angular velocity is about 50 deg/s. Most of the muscle-level stimuli show good consistency with the body-level stimuli. For example, near the maximal elbow joint angle, the resistance force, active and passive muscle fiber force, and length change of muscle fiber reach their maximum or minimum at the same time and their curves show a good consistency. But because of the differences in muscle architecture, the muscle

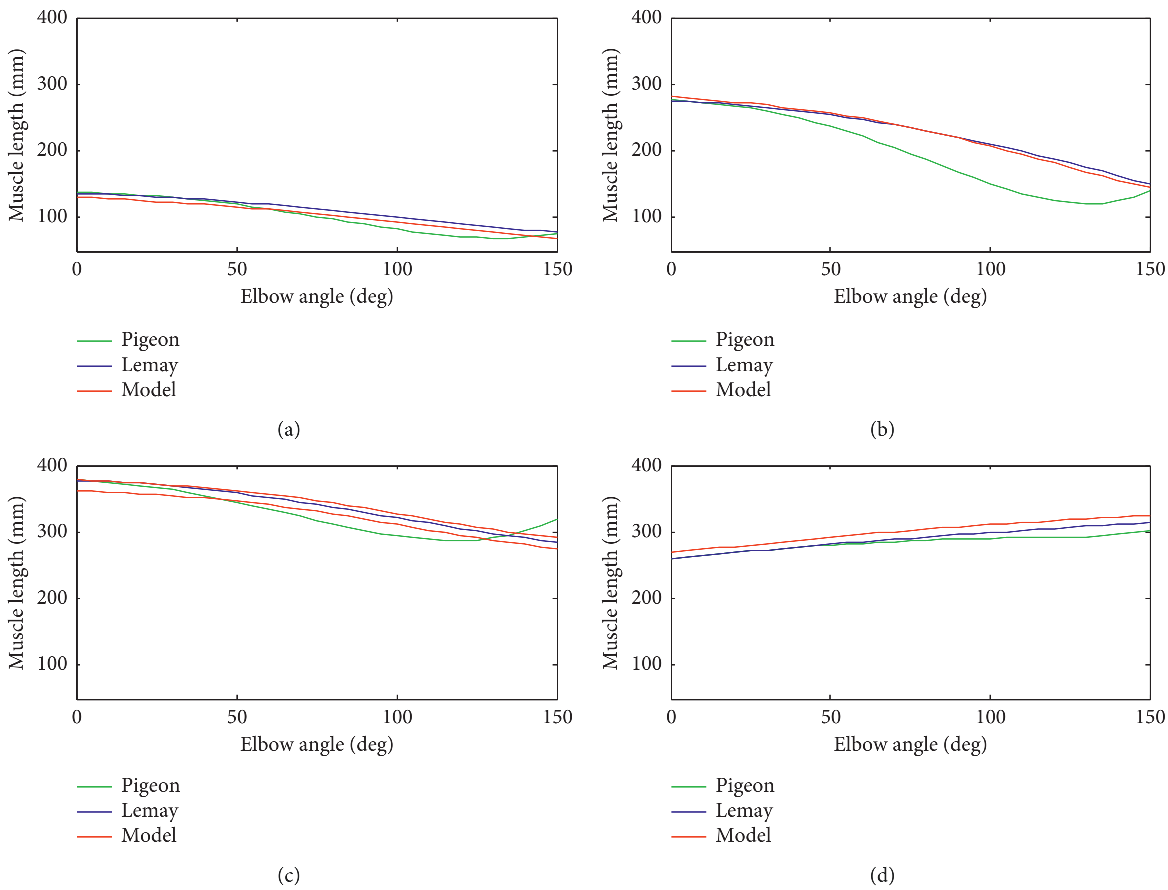

Figure 9: Comparison of muscle length as a function of elbow joint angle. (a) BRA (b) BRD (c) BIC (d) TRI.

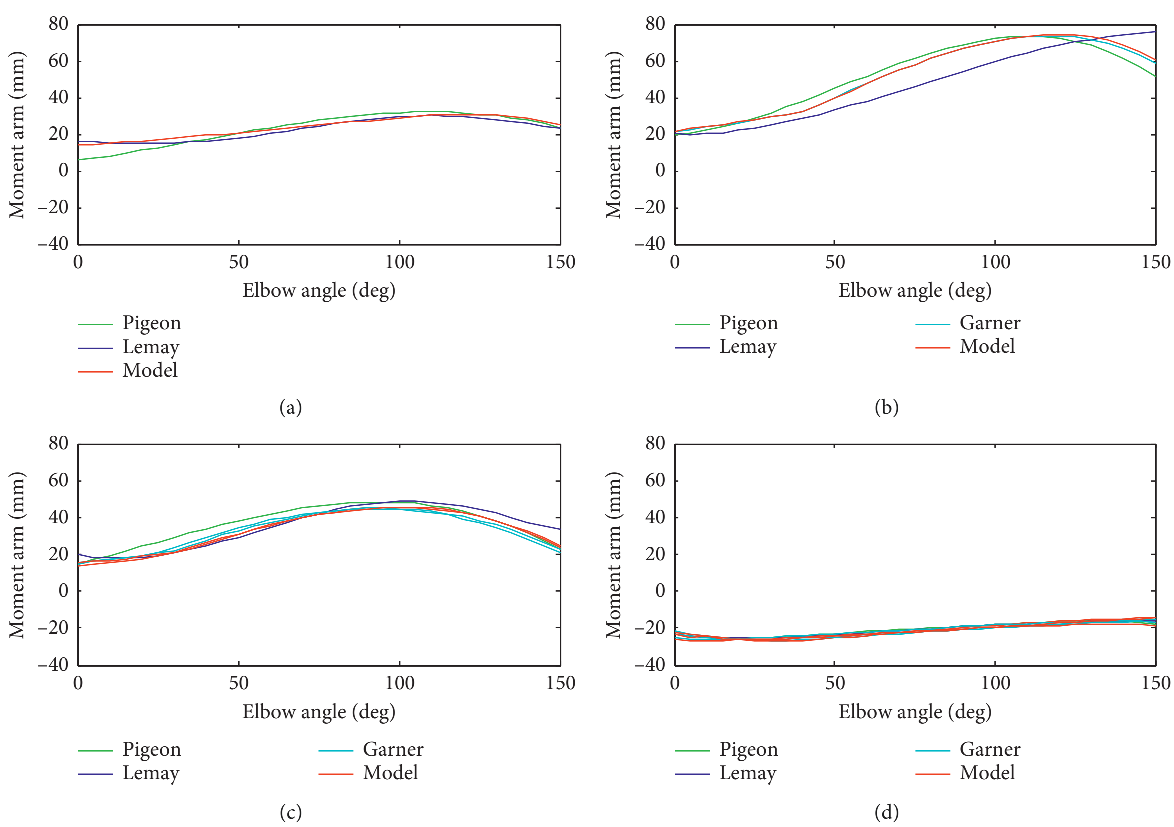

Figure 10: Comparison of moment arm as a function of elbow joint angle. Positive values indicate flexion moment arm and negative values indicate extension moment arm. 0° means the elbow is fully extended. (a) BRA (b) BRD (c) BIC (d) TRI.

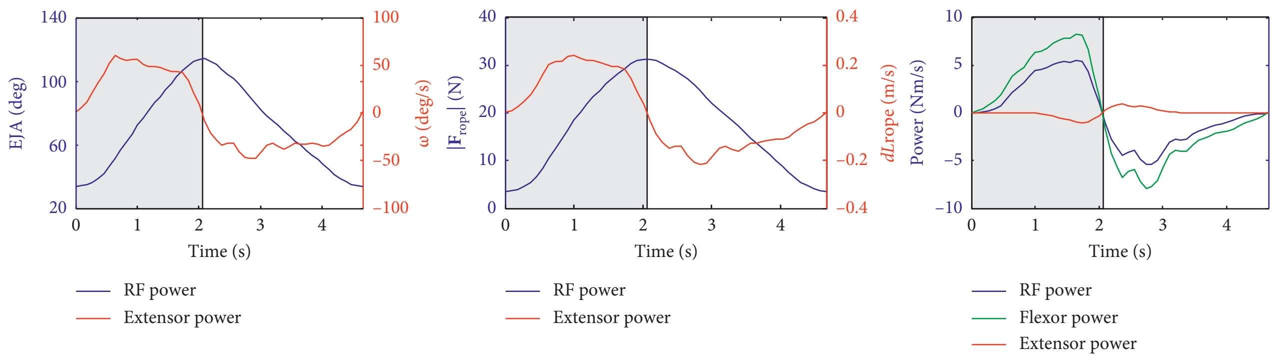

FIGURE 11: The elbow joint angle (EJA), angular velocity (ω), resistance force ($|\mathbf{F}_{\text{rope}}|$), length change rate ($dL_{\text{rope}}$), power of resistance force, power of flexor, and extensor in the training.

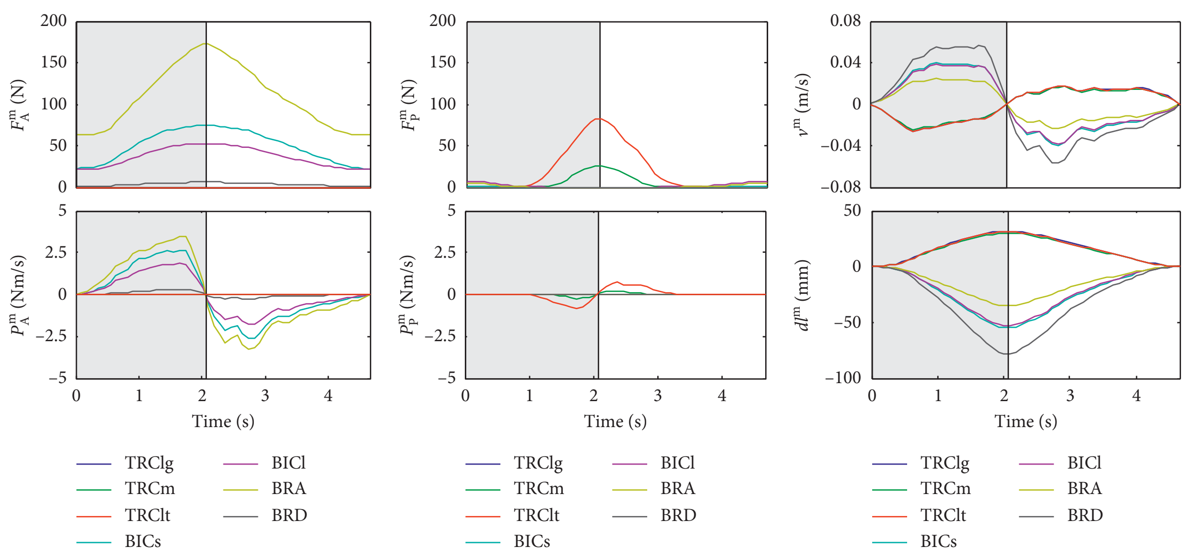

FIGURE 12: The active ($F_A{}^m$) and passive ($F_P{}^m$) muscle fiber force, muscle fiber velocity (v^m), power of active ($P_A{}^m$) and passive ($P_P{}^m$) muscle fiber force, and length changes of muscle fiber in the training.

fiber velocity shows a significant difference between flexor and extensor, and the curves of muscle fiber velocity are different from the curve of angular velocity. The resistance force power can be considered as the combined effect of flexor and extensor power. Passive muscle fiber force, which appears when the fiber length exceeds its optimal fiber length, affects active muscle fiber force of other muscles. BRA was the biggest energy provider and produced the biggest average and maximal force; this is probably because BRA possesses the biggest PCSA among flexor.

4. Discussion

Simplicity and usefulness are two important features of the system. The only training device required in this system is a fitness tube with a load cell which was designed to measure the resistance force. Combining the resistance force with the established models, the mechanical states of muscles can be roughly estimated and monitored during the training. Many studies reveal that muscle velocity and muscle power (the product of force and velocity) are critical determinants of physical functioning in older adults [10], and the velocity loss is an indicator of neuromuscular fatigue during resistance training [36]. As shown in Figure 13, we built a GUI to help the users type in the initial setup of the experiment and interact with the MSM. The real-time interaction makes the MSM like a sensor which can be used to measure muscle kinematic parameters such as muscle length changes and muscle velocity (v^{mt}). Through the GUI, the patient can see the velocity change of his muscle and choose the appropriate training dose and intensity based on his feeling or the instruction of the physiotherapist. Visual interaction increases the patient's interest in the training process. Maximum muscle velocity and other mechanical stimuli (such as maximum RF, power, and work) can be used as relative indicators for recording the training phase or setting training goals.

This study presents some limitations. Due to the intrinsic property of static optimization, the optimized MTF is closely related to the objective function and constraint conditions. Without changing the muscle architecture in the model, experiments were conducted on two other participants with different heights and weights. The calculation results show

Table 2: Work, maximal change in length, and average and maximal force of resistance force and muscles. We set the direction of elongation along the rope or muscle path as the positive direction of force and length change.

	$\vert\mathbf{F}_{rope}\vert$	Extensor			Flexor			
		TRClg	TRCm	TRClt	BICs	BICl	BRA	BRD
Work (N∗m)	−6.24	0	−0.105	−0.502	3.06	2.02	4.03	0.308
Maximal change (mm)	316.04	31.61	30.13	31.34	−55.08	−52.99	−34.89	−78.10
Average force (N)	−17.34	0	−4.98	−20.19	−49.58	−36.62	−109.12	−3.43
Maximal force (N)	−31.27	0	−26.21	−82.76	−74.13	−52.42	−171.93	−5.94

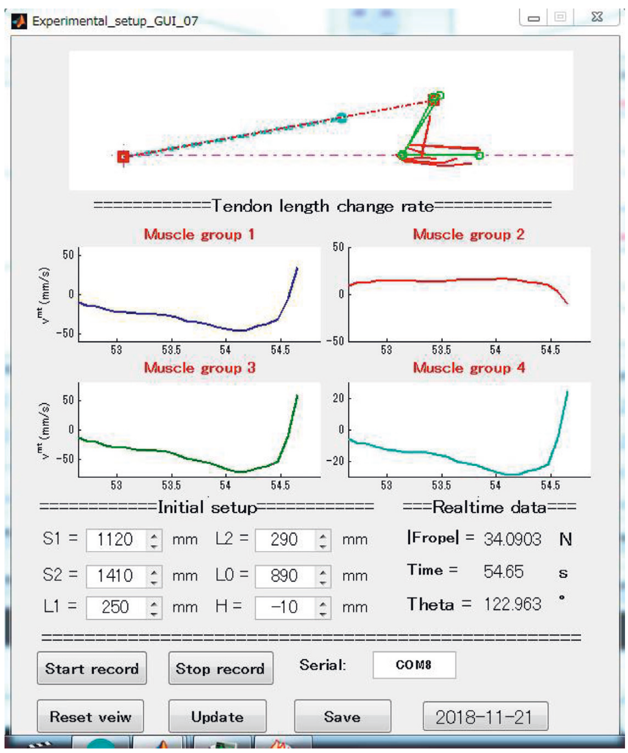

Figure 13: The GUI which is built to show the MSM, muscle velocity (v^{mt}), initial setup, and some real-time results. A subject was extending his forearm and the muscle velocity changes over time were showed to the users (muscle velocity reflects the state of muscle shortening and stretching. Less than 0 means muscle shortening, and more than 0 means muscle stretching). Muscles were divided into four groups, and the muscle velocity of each group is the average muscle velocity. BICS and BICl belong to Group 1. TRClg, TRClt, and TRCm belong to Group 2. BRD belongs to group 3, and BRA belongs to group 4.

that the measurement system can correctly estimate the angle of the elbow joint, but the muscle activation patterns are almost the same when the elbow flexes and extends. Differences are the measured resistant force and angular velocity of the forearm. However, the generic MSM is sufficient to provide reliable indicators to record relative changes of training intensity at different training stages. Comparison between estimated force and surface electromyographic signals of muscle is planned for future work to show the extent to which the optimized MTF reflects the actual muscular states. And because the elbow flexing and extending was limited in the sagittal plane, the muscle activation patterns are relatively simple in the movement. Future work also needs to enhance the system to include more degrees of freedom in the MSM and apply it to other types of resistance exercises like elbow extensor resistance training and pull-ups.

5. Conclusion

This paper presents the concept of using musculoskeletal modeling to estimate muscular states during elbow flexor RT for bedridden patients, and it is mainly on the discussion of computational methods. We take the elbow flexor RT as a simple example, and an integrated system was built for this exercise. The design concepts of the system, the measurement, and analysis methods were described in detail. We recorded the video about the training process and measured the real elbow joint angle by using a protractor and compared it with that estimated in EJAEM. The results demonstrate that the measuring system can correctly estimate the elbow joint angle when the forearm flexes or extends in the sagittal plane. The muscle length and muscle moment arms were calculated and compared with results provided in other references to show that the established MSM is adequate to serve as a generic model to analyze muscle kinematics in the case of elbow flexing or extending in the sagittal plane. The system offers a simple method to monitor muscle states during elbow flexor RT in bedridden patients, providing coaches or physiotherapists with practical muscle-related information to evaluate the training process. The calculations also demonstrate that the musculoskeletal modeling is a considerable method to vividly analyze the muscular states during training.

Abbreviations

EJAEM: Elbow joint angle estimation model
MSM: Musculoskeletal model
MTF: Muscle-tendon force
MTM: Muscle-tendon model
RT: Resistance Training.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

No potential conflicts of interest were reported by the authors.

Supplementary Materials

Supplementary material file for the video clip about the GUI of the integrated system in which a healthy subject was asked to perform two sets of concentric and eccentric contractions and some real-time results were displayed to audience via the GUI. (Supplementary Materials) (*Supplementary Materials*)

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