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Asymmetrical Performance and Abnormal Synergies of the Post-Stroke Patient Wearing SCRIPT Passive Orthosis in Calibration, Exercise and Energy Evaluation

Yun Qin*, Naila Rahman and Farshid Amirabdollahian

School of Computer Science, University of Hertfordshire, Hatfield, Hertfordshire, UK

Abstract

In the context of therapeutic human-robot interaction, it is important to detect human contribution in interaction with robots, thus to auto-tune a robot to compensate or resist based on such input. A passive orthosis is used to evaluate interaction based on kinematic data and energy flow model to identify human-contributions during interaction experiments with healthy subject and stroke patient. The results identified presence of abnormal synergies between wrist and fingers, showed a skewness apparent in stroke patient performance which seemed to decrease over-time after the rehabilitation practice and indicated lack of fine control. We hypothesise that the presented methods can be used as potential performance benchmarks allowing to identify subject's contribution during an interaction session but also to observe extent of fine motor control over time.

Keywords: Energy flow; Passive orthosis; Stroke rehabilitation; Abnormal synergies

Introduction

Stroke can cause damages to motor regions in the brain resulting in loss of control to upper and lower limbs. The impairment after a stroke event including weakness of muscles, abnormal muscle tone, damage of motion range, abnormal movement synergies and loss of sensation, has an influence on quality of life and activities of daily living [1-3].

Using robot-mediated rehabilitation has witnessed twenty-five years of development [4-7]. The functions of the robotic rehabilitation systems have varied among delivering repetitive trainings to relearning lost motor skills. Studies have mostly focused on repetitive training of reaching tasks for upper limb, while wrist and hand training has been more limited due to the inherent complexity of designing grasping tools. Hesse et al. developed a robot-assisted arm trainer for the passive and active practice of forearm and wrist movements in hemiparetic subjects and this research showed promising results while making intensive training of elbow and wrist possible [8]. In a different study, a wrist extension has been designed to complement the MIT-MANUS robotic device for the proximal arm (InMotion ARMTM) [9]. This study showed promising results highlighting added benefits of wrist exercise after a period of 6 weeks training. A further study from this group investigated if administering six-weeks of hand and wrist therapy before six-weeks of shoulder and elbow had a different outcome compared to a reverse order (shoulder and elbow first, then hand and wrist). While the clinical scores between the two approaches were similar, the study showed that in terms of generalizability and transfer of skills, training of the distal limbs led to twice as much carryover effects [10]. After stroke, wrist, hand and fingers extensions are often especially affected, and these are often the last symptoms to show some improvement. Therefore, a training environment for distal control for grasping and manipulation of objects has a large potential in contributing to such improvements.

Different methods including unactuation, passive actuation and active actuation have been widely used in the robotic post-stroke rehabilitation systems. Carmeli et al. proposed an unactuated device HandTutor which also provided visual and auditory feedback [11]. Passive actuators have also been used in rehabilitation systems. Springs were involved in the orthotic aided training SaeboFlex device developed by Farrell et al. [12]. Functional electrical stimulator which triggers muscles in the hand and wrist has been used in neuro-rehabilitation [13]. Loureiro and Harwin presented a 9-DOF reach and grasp device for neuro-rehabilitation [14]. A hand-wrist robotic manipulator with electric motors was developed by Takahashi et al. [15]. These studies focused on multiple approaches to hand and wrist rehabilitation, while with the exception of SaeboFlex, none were developed with the particular aim of supporting home-based rehabilitation.

The SCRIPT (Supervised Care & Rehabilitation Involving Personal Tele-robotics) project, partially funded by the European Community focuses on improving recovery gains of hand and wrist for chronic stroke survivors through larger repetitions and frequent exercises [16]. A home-based device SCRIPT passive orthosis for the hand and wrist rehabilitation [17] is delivered together with several interactive therapeutic exercise games operated by different movements such as flexion and extension of the wrist and fingers [18].

In the SCRIPT project, we utilize detailed knowledge on measures of energy and energy flow from the participant to the orthosis or vice versa which is essential to identify the extent of 4 human contribution during an interaction session. We rely that awareness of human contribution makes the interaction more meaningful and personalized. We hypothesise that such knowledge provides a good indicator for changes in ability to isolate movements of wrist and fingers during hand and wrist articulation and can thus be used as an indicator in assessing recovery. Mak, Gomes and Johnson proposed a model to

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***Corresponding author:** Yun Qin, Adaptive Systems Research Group, School of Computer Science, University of Hertfordshire, Hatfield, Herts AL10 9AB, UK, Tel: +447850065319; E-mail: qinyun19850803@hotmail.com

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study the interaction between a patient and a rehabilitation robot and their study showed the potential for interpreting changes during rehabilitation [19]. Tzemanaki et al. developed a robotic system for stroke and post hand-surgery patient rehabilitation which allows patients to gradually regain flexibility in their finger-joints by passive extension and flexion of their fingers and dynamic models of a human hand have been derived by their research [20].

In order to auto-tune an orthosis to compensate or resist for the therapeutic human-orthosis interaction, identifying the human contribution in interaction with orthosis is crucial. In this paper, the evaluation of the SCRIPT passive orthosis interaction based on raw kinematic measures, temporal aspects of movement and an energy flow model is used as a proof of concept highlighting applicability of these approaches in identifying human-contributions. An interaction experiment is conducted and discussed in support of this proof of concept study. The structure of the paper is as follows. In the Introduction, the SCRIPT system and its training environment is briefly introduced. The experiment plan is introduced in the Material and Methods. The motion comparison results for the healthy subject and stroke patient during calibration and an exercise game are discussed and the energy flow evaluation results for both subjects are also presented in the Results and Analysis. Then discussion is given in Discussions.

Script system

The SCRIPT tele-robotic upper-limb rehabilitation system as shown in Figure 1 consists of a passive hand, wrist and forearm exoskeleton customised to patient's hand-size [1] mounted on a Saebo Mobile Arm Support [21] and attached to a Windows based personal computer (PC) which allows patients to interact with a range of therapeutic motivational games using their affected upper-limb. The patient's therapy is planned and monitored offline remotely by a healthcare professional using a dedicated interface.

SCRIPT device

Leaf springs and elastic cords are used to apply passive torques to assist extension of the five fingers. Use of elastic bands allows the passive torques to be varied depending on the degree of weakness exhibited by the patient. A potentiometer is used to measure the angle of wrist extension and flexion. Flex sensors are used to measure the flexion of the fingers. An Arduino Nano microprocessor board is used to sample and convert data from the potentiometer and flexion sensors from analog to digital values. An inertial measurement unit (IMU) is used to measure pronation, supination and three-dimensional position of the hand.

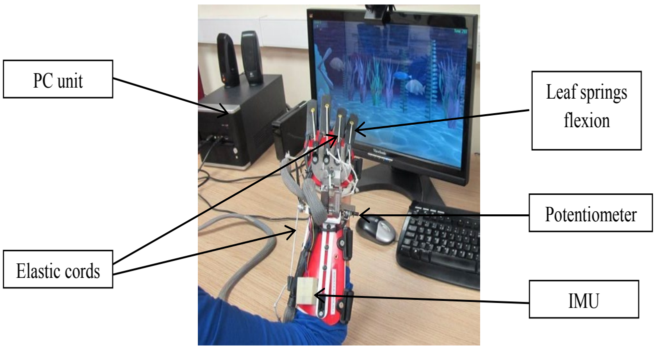

Figure 1: SCRIPT system

In order to allow standardisation, each device is calibrated to ensure that raw digital data is converted into normalised values that provide joint angles. The range for normalised angles for the wrist and fingers is from zero to ninety degrees.

SCRIPT patient PC training environment

The patient training environment allows users to complete a training plan prescribed by their therapist, to monitor their own progress and to communicate with the therapist. The training plan consists of interactive therapeutic motivational games [22] which are controlled by the patient while wearing the device.

A server process on the PC acquires data from the SCRIPT device at 30 Hz and processes it to recognise hand, wrist and arm movements or gestures. Due to the passive nature of the device, the sampling rate of 30 Hz was seen as adequate for this interaction. The time-stamped device data and recognised gestures are stored in a normalised MySQL database. The gesture data is sent to a game server process and is used to control games.

Game calibration: The range of motion exhibited by people after stroke varies significantly from healthy individuals and is mainly dependent on the degree of loss of motor function. However, the range of motion for a patient is not static, as there may be an increase due to recovery or a decrease due to fatigue or lack of motivation.

Before each session of the game, the participant is required to perform a few repetitions of a movement such as fingers and wrist flexion and extension under a calibration procedure. The purpose is to record a baseline measure prior to each exercise session, while providing a chance to make the game adaptive to the level of subject's available range of motion on the day. The procedure analyses the duration and amplitude of the ranges recorded. During these calibration steps, the user is instructed to perform, in isolation, gestures used to control a game. The device data readings are then used to determine minimum and maximum values of joint angles and to recognize valid gestures during game play. During the exercise game, the fingers flexion and extension postures can be detected according to the subject's personalized 7 range of motion measured during calibration. On the other hand, the calibration also makes sure that the participant exercises in a range close to 90% of his/her active range of motion at an achievable speed which prevents the game from being too easy or too challenging. The gestures calibrated are the hand/wrist flexion and extension, forearm lateral movements (left and right movement of the forearm), forearm pronation and supination and hand drop and lift.

Motivational therapeutic games: The overall objective of the SCRIPT project is to encourage patients to perform multiple repetitions of functional movements with their affected arm and hand for at least 180 minutes each week. In order to keep the patient motivated and engaged, the system provides therapeutic games for training. The current phase of the project provides three games: Sea Shell; Super Crocco and Labyrinth. There are three variants of the Super Crocco and Labyrinth games, designed to encourage the patient to perform increasingly difficult functional movements as they recover motor function. This follows the Gentile's taxonomy [23] starting with movement with simple functions, such as fingers flexion and progressing towards gestures performed in motion i.e. lateral movement of the hand while grasping a key. The architecture also allows new games to be added to the system. Figure 2 presents the SCRIPT calibration screen and the Sea Shell game.

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Before playing each game, the user is required to perform a calibration step. The game is then played in five minute blocks and the user is advised to rest between blocks.

Material and Methods

As a proof of concept study, one healthy participant and one patient recovering from stroke were considered for this initial comparative study. The healthy participant was recruited from the University of Hertfordshire, United Kingdom under the ethical approval number COM/ST/UH/00006. The stroke patient was selected from the pool of participants currently undertaking a 6 weeks summative evaluation ethically approved by the Medical Ethics Committee under approval number NL42483.044.12. Patients included in the summative study were chronic stroke (>6 months after stroke) with unilateral ischemic or haemorrhagic stroke between 18-80 years old, clinically diagnosed with central paresis of the hand. They had a minimum of 15 degrees of elbow flexion, with about a quarter range of finger flexion with a fair cognitive level to allow them to read, understand and follow instruction. Both participants provided a signed informed consent.

The main objective of this experiment was to compare the calibration and game play data recorded during one interaction session, between the two participants. The healthy participant, coded as S1 in this study only completed one interaction session with the SCRIPT device as required. Participating patient, coded as S2, was involved in the summative evaluation and played the Sea Shell game in different sessions among the six weeks. Session 1 of the game is the first session among the six-week period when S2 started to play the game for the first time. The reason for picking up this session is to make sure both participants had the same extent of familiarity with the system within a session, which correspondingly lasted for five minutes. Another set of S2 game playing data was collected during session 11 after the subject had played ten sessions of Sea Shell game. This was to monitor if any changes in interaction parameters could be observed over time and with increased familiarity. The 9 choice of first and last session is similar to a large number of clinical studies in robotics for rehabilitation where pre and post intervention indicators are compared. The spatial features, temporal features and flow of energy are compared by the numerical data deriving from bending sensor and the numerical result of energy flow calculation. Table 1 highlights study schedule and sessions used to extract data in support of this experiment.

Results and Analysis

Recorded interaction data for this experiment was extracted from the MySQL database used to store data. These were used to conduct the next three analyses.

Comparison during calibration phase

The calibration procedure provided the user's baseline range of motion. The comparable experiment was done between the two subjects when they did the calibration for the first time. The calibration for S1 lasted for 8.5 seconds, while the calibration for S2 in session 1 lasted for 25 seconds until the SCRIPT system was able to recognize the range of motion. Due to the high similarity among five fingers, the result for one finger is illustrated in this paper. Figure 3 provides an observation of the index finger and wrist flexion angle when the participant was asked to perform only finger flexion and extension.

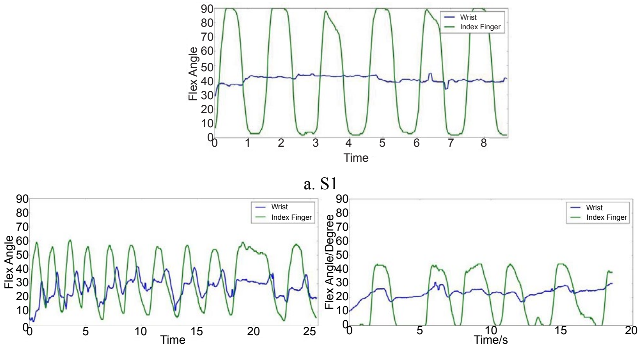
From Figures 3a and 3b, we could see that S1 is able to achieve 90 degrees range of motion and on the contrary to that, S2 had a limited range of motion up to 60 degrees. Regarding the temporal aspects, if we only focus on the time between start to the 8.5 seconds, S1 10 accomplished six rounds of finger flexion and extensions and S2 only finished five repetitions. From Figures 3b and 3c, the SCRIPT system took 18.6 seconds to recognise S2's amplitude of the motion range in session 11, compared to 25 seconds in session 1. These two figures highlight that with increased familiarity of the game, S2 has improved in performing the calibration procedure.

Figure 3 also shows the index finger and wrist flexion angles when the participants were directed to do only the finger flexion and extension. From Figure 3a, it is notable that S1 had the ability to near perfectly isolate the movement of the finger and wrist and s/he exactly did the required movement where the index finger flexed and extended while his wrist was kept at a fixed position. Based on Figure 3b, each local maxima and minima of the Index Finger curve was followed by the flexion/extension of the Wrist. The index finger movement of post-stroke patient was accompanied by the wrist movement.

Comparison during game play

The therapeutic objective of the Sea Shell game is to encourage patients to extend and flex their wrist and fingers. The game manoeuvres a sea shell to catch fishes underwater by opening and closing the sea shell. The goal of the game is to catch as many fishes as possible when the fishes arrive near the sea shell. The sea shell opening and closing is operated by flexing and extending fingers. Considering post-stroke patients tendency to flex their wrist due to an inability to relax the flexors or to engage the extensors sufficiently [1], the game is also designed to encourage the patient to extend their wrist before presenting finger flexion/extension sufficient to catch a fish. When the wrist is flexed for a certain threshold duration (50% of the range of motion), the sea shell falls into sleep thus unable to catch any fishes

Figure 2: SCRIPT calibration and Sea Shell game environment



a. S1

b. S2, Session 1

c. S2, Session 11

Figure 3: The flexion angle during finger flexion and extension calibration

	Calibration 1	Game 1	…	Calibration 11	Game 11
S1	☑	☑			
S2	☑	☑		☑	☑

Table 1: Participants completed sessions used for this experiment

thus encouraging wrist extension prior to flexion of fingers .

The flexion angles of index finger and wrist during Sea Shell game for the healthy subject (session 1) and post-stroke patient (sessions 1 and 11) are illustrated with respect to time in Figure 4a-4c. When one target (fish) appeared on the screen, subjects might perform several grasping movements until they felt confident for successfully catching the fish. Each grasping movement was corresponding to one visible peak in the graph. The movement of the subjects for a given target hit (fish caught) might include a position profile with multiple convexity.

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From Figure 4, it can be found that in a 100-seconds window selected arbitrarily, S1 was able to perform 23 successful grasping and S2 could only perform 11 successful grasping. After the ten sessions training, the total successful grasping achieved by S2 was 18. This presented an increase of 64% in game performance over a period of 10 sessions as reflected by the number of grasping. The abnormal synergies of the index finger flexion movement and wrist flexion movement for S2 can also be observed in Figure 4. Figure 5 presents one of the convexities magnified in a new time-window starting from zero.

From Figure 5a, it is trivial to notice that for S1, his/her index finger flexion angles during flexion and extension were highly symmetrical. Figures 5b and 5c shows that S2's index finger flexion angles were asymmetrical for flexion and extension with respect to its mean. Furthermore, we use skewness to reflect the extent of asymmetry as

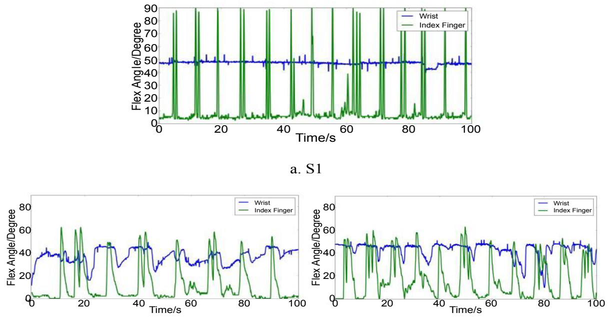
By calculating the skewness for the data set of index finger flexion angles of S2 game playing session 1, the Index Finger curve was positively skewed with the skewness of 0.424. While the skewness for the S1 was very close to zero (0.004). After ten training sessions, the skewness for the data set of S2's index finger flexion angles in Sea Shell game playing session 11 was 0.171.

Energy flow evaluation

By using the similar approach as of Mak et al. [19], the energy amount and energy flow for the index finger and wrist for post-stroke patient and healthy subject during Sea Shell game playing is compared in this Results and Analysis. Fingers flexion angles were recorded by the five bending sensors and the wrist flexion angle was measured by the potentiometer in the SCRIPT device and the force applied by the elastic band to the finger tips was calculated using the modulus of elasticity. The known parameters also included the length, velocity, acceleration and mass of the fingers and palm. This allowed the authors to derive complete forward kinematic and dynamic models for the hand-orthosis system. Newton-Euler formulation was used to analyse the forward dynamic behaviour of the hand-orthosis system and balance of linear forces and balance of moments equations of the fingers and wrist were built up, respectively.

In the numerical evaluation, the data were digitally low-pass filtered with a 3rd-order Butterworth filter and passed through the formulation to calculate finger and wrist moments during the Sea Shell game. For the purpose of this comparison, one successful grasping was selected and data from this interaction was used within the calculation to obtain a moment/moment plot for finger and wrist flexion/extension. Pre-post comparison of the energy flow evaluation for the patient was accomplished to investigate his improvements between the first and last sessions. The energy involved during S1 game playing and S2 game playing in sessions 1 and 11 is illustrated in Figure 6.

From Figure 6a, the Flexion curve for S1 was smooth and one crossover happened temporarily when the index finger nearly reached the maximum flexing position and the Extension curve was also relatively smooth for this participant. From Figures 6b and 6c, we could see that there was one more peak in the Flexion curve compared to the

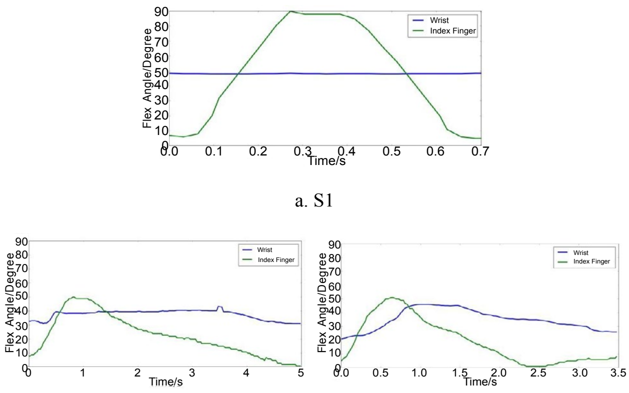


a. S1

b. S2, Session 1

c. S2, Session 11

Figure 4: The flexion angles during Sea Shell game

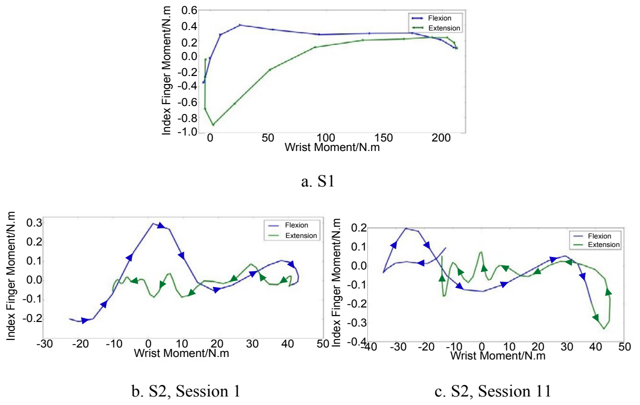


a. S1

b. S2, Session 1

c. S2, Session 11

Figure 5: The flexion angles during one grasping in Sea Shell game



a. S1

b. S2, Session 1

c. S2, Session 11

Figure 6: The energy involved in game play

S1 and there were many local maxima and minima in the Extension curve.

Discussions

Comparisons between S1 and S2 during calibration highlighted longer calibration time required by S2, and S2's calibration time became shorter after 10 training sessions compared to the beginning of his exercise, while within a normalised time window, S1 had achieved more repetitions of the flexion and extension task. The calibration data allows us to monitor person's status prior to game play and here highlight patient compliance, either due to becoming more familiar with the SCRIPT1 system and games, or due to changes in their underlying recovery trends.

More interestingly, it was observed that S1 was capable of limiting wrist movements while performing the hand flexion while S2 presented abnormal wrist synergies during the grasping gestures in calibration session 1. Importantly, this seems substantially improved during calibration 11. Session 11 presented a picture closer to that of the healthy subject, with better control over wrist flexion, during flexion of the fingers, highlighting a reduced level of abnormal synergies.

When game play was considered for the comparison, S1 presented better performance as reflected by the number of grasping, while S2 presented an improvement of over 64% in achieving interaction objectives when comparing session 1 to session 11. Again, this could be due to compliance related to familiarity or underlying recovery.

With a closer look into game play based on temporal properties of the movement, it was observed that a positive skewness was apparent in S2 game play, which could potentially effect successful catching of the fishes due to bad timing of the sea shell opening and closing. However, an improvement was also observed based on this parameter when comparing sessions 1 and 11. The skewness parameter indicated a reduction towards that of the healthy subject. This parameter can be applied to each movement thus providing more insights into movement's symmetry. It is thought that movement asymmetry is a good measure of movement coordination [24] thus this parameter can inform us regarding improvement in the extent of movement coordination after successive game play sessions.

When energy flow modelling was used, S1 presents a clearly well-controlled grasping while wrist activities are kept to a minimum, while S2 presents synergistic wrist moments during flexion of the hand. More interestingly, here we can observe a difference between Flexion and Extension, indicative of better controlled flexion of the fingers when compared to the extension. This is in line with observations by Cruz et al. [25] highlighting difficulties in finger extension tasks after stroke, when compared to finger flexion. Surprisingly, this parameter also shows improvement at the level of finger moment vs wrist moment variation at session 11, which is in line with the observations made when comparing spatial and temporal features of the movement.

Another notable observation here is that S1 wrist moments during extension remain on the positive quadrant, while S2 wrist moments vary from positive to negative moment. Here reduction in wrist moment is associated with the extension assistance provided by the wrist extension elastic cord. The assistance provided by this cord is at minimum for a fully extended wrist. Moreover, finger moments present more fluctuations when compared to the wrist. These indicate exchange of energy between the device and the patient during finger extension, clearly indicating device's contribution in assisting a full extension.

Presence of abnormal synergies have been observed and classified by other studies for example work from Dewald et al. [26] presented shoulder and elbow abnormal synergies identified using EMG electrodes while Dipietro et al. hypothesised that changes in the proximal arm abnormal synergies could be potentially used as a measure of recovery [27]. This study focused on the distal arm and identified multiple areas where presence of such synergies is visible. The current study has the limitation of small subject numbers and relatively short follow-up period. In order to identify changes in abnormal wrist and hand synergies over time, the current study is being extended to include a larger sample size of healthy volunteers and stroke patients using the system over time, while also considering session-by-session improvements during a clinical evaluation of 24 stroke patients. The 16 intention is to identify any supporting evidence for reduction of abnormal synergies over time. We intend to consider the characteristics of the moment/moment plots, e.g. number of local minima and maxima and the area under the curve, to further expand on the usefulness of this approach for wrist/hand interactions. We also intend to further explore the use of skeweness as a measure of improvement in movement coordination, as it can reflect on the extent of fine control, leading to successful achievement of game objectives. Furthermore, considering change of moment alongside changes in active range of motion, so moment/angle plots is another dimension for our future investigations.

Conclusions

In this paper, finger motion during calibration and game play as well as the energy involved in the game play were compared between a healthy subject (S1) and a post-stroke patient (S2). By comparing the index finger flexion angle during calibration, we found that the post-stroke patient had a reduced (2/3) range of motion for the index finger compared to the S1 and the speed of the movement for the S2 was slower than S1. After analysing the data during the game play, it was notable that the S2 presented index finger flexion angles that were asymmetrical for flexion and extension motion. Skewness was used to reflect the extent of asymmetry and movement coordination and showed improvements between session 1 and session 11. The index finger movement of the S2 was always accompanied by the wrist movement in both calibration and game playing and this indicated the presence of abnormal synergies.

The energy amount and energy flow of the index finger and wrist for both subjects during game playing were also evaluated. The resultant moment/moment plot for S1 was generally smooth and only had one temporary crossover when the motion changed from flexion to extension hinting on momentary wrist involvement. Given that many local maxima and minima were present for S2, we concluded that these are linked to the patient's inability to control the finger flexion in isolation with wrist, while highlighting the device effect in extending the fingers using elastic cords. Our results are evidence for the presence of abnormal synergies. Furthermore, we found that S2 had worse control for the extension process than flexion process, which was anticipated.

The asymmetrical performance between flexion and extension and abnormal synergies for higher number of post-stroke patients will be analysed in future work. Furthermore, changes in angle/moments are considered for further explorations towards identifying positive changes in the extent of movement over time. We also aim to explore the lack of ability to control as a benchmark to evaluate the rehabilitation recovery and improvement of using the SCRIPT system.

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