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Research Article

Ranges of motion as basis for robot-assisted post-stroke rehabilitation

[1]Kinga A. Major, [2,3] Zoltán Z. Major, [4]Giuseppe Carbone, [5]Adrian Pîslă, [5]Calin Vaida, [5]Bogdan Gherman, [5]Doina L. Pîslă

[1] Cluj County Emergency Clinical Hospital, IInd ICU, Neurosurgery Clinic, Cluj-Napoca, Romania; [2] "Iuliu Hațieganu" University of Medicine and Pharmacy, Cluj-Napoca, Romania; [3] Municipal Clinical Hospital Cluj-Napoca, Neurology Department, Romania; [4] Laboratory of Robotics and Mechatronics, DiCEM, University of Cassino and South Latium, Italy; [5] Research Center for Industrial Robots Simulation and Testing, CESTER, Technical University of Cluj-Napoca, Romania

All authors had equal contribution

Abstract. Background: Stroke is a highly disabling disease, requiring a long and costly rehabilitation. Rehabilitation robots might represent a cost-effective solution. The present technical means for rehabilitation don't match all the requirements for post-stroke recovery. This work describes the analysis of human motion ranges aiming at the design of a cost-oriented and user-friendly post stroke robotic rehabilitation solution. Materials and method: The study was performed on a group of 21 patients, 11 females and 10 males, matched with the ischemic stroke affected population from the point of view of age and comorbidities. The motion range measurements were made using a standard goniometer. Shoulder flexion, extension, abduction, adduction, elbow flexion, pronation, supination, wrist flexion and extension, metacarpal-phalangeal, proximal and distal inter-phalangeal flexion was measured, in a comparative fashion for the right and left side, for males and females and for elderly and young patients. Results: First, no significant side-dependent differences were identified. Sex seems to have an importance: female subjects having a significantly higher motion range for some of the measured joints. Age impacts the motion amplitude also, elderly having stiffer joints, lower motion ranges. Conclusion: The results of this preliminary analysis underline the necessity of developing an open ongoing database to refine the exact motion ranges, and the main effects influencing these intervals in order to get a feasible input for a biomechanical motion concept of a future rehabilitation robot.

Key Words: stroke, range of motion, robot, rehabilitation.

Corresponding Author: Z. Z. Major, e-mail: zoltan.major@eeg-emg.ro

Introduction

Ischemic stroke is a common health issue, causing major disability, being detrimental from individual, familial and societal perspectives. 80% of patients experience paresis of the upper limb and only a minority fully recovers. In such cases, it is very important to provide efficient and cost effective post stroke rehabilitation (PSR), either by classical physical therapy or using rehabilitation devices (Beebe & Lang 2009), the rehabilitation process having a large financial impact.

Rehabilitation is a lifetime commitment. Classical physical therapy uses gonio- and dynamometric measurements in order to quantify the limitations of motion and reduction of muscle strength, to correctly evaluate disability. This helps to design appropriate therapeutic interventions, and assess effectiveness (Hirschhorn et al 2015). The same pre-evaluation is required for rehabilitation devices also.

Post-stroke anti-gravity active range of motion values can be considered indicators of the capacity of the spared motor system to activate the spinal motor neuron pools that move a given limb segment. The clinical perception about individuals who have recently suffered a stroke is that paresis of distal segments is more severe than proximal, or at least is unequal, raising the necessity for both holistic and segmental approach (Beebe & Lang 2008).

There are many physical therapy techniques developed to assess and treat a patient after stroke, the Bobath concept being widely accepted in neurological rehabilitation of the motor control by promoting motor learning in different environments. Regaining the postural and movement control is the main goal for the stroke patients. The therapists conduct the rehabilitation by trying to correct abnormalities, both by passive posturing and by correcting limitations of active movement (range of motion and strength) (Gjelsvik 2008). Usually this requires a long period – several months to a couple of years – of continuous therapy. Even if only stroke is considered as a disabling factor, there are clearly insufficient physical therapists, and even if there were, the costs would be unaffordable for the society. Human resource deficits or unsustainable costs might be managed by using highly specialized medical robots, at least for repetitive parts of the rehabilitation, suitable for robot assistance.

The robot market shows a dynamic development, both for industrial and service robots. From the latter, medical robots are representing a promising field, many companies being involved already in the robotic rehabilitation (H2020 – Robotics, Multiannual Roadmap for Robotics in Europe 2016). Their products are targeting the assistance and automation of physical therapy (Executive Summary World Robotics 2016 Service Robots 2016). Service robotics is attracting more and more interest and several solutions are currently under development (Wang et al 2016; Copilusi et al 2015) specifically in the field of medical robotics and rehabilitation (Cordero et al 2014; Carbone et al 2010).

Due to technical difficulties, a rehabilitation robot cannot reach the complexity of the human approach on a disabled limb. The concept to develop such a device must clearly define its borders in order to remain practical and feasible. Therefore, a careful analysis of human motions is needed to achieve a novel biomechanical model for cost-oriented user-friendly design solutions. The proposed model offers a simple and realizable approach, preserving the functionality of the upper limb. The range of motion values result from the development of an open database, which will be used as a first input for our model of a robotic rehabilitation device.

The proposed model

"The purpose of the upper limb is to allow the hand to be placed in various positions to accomplish a multitude of tasks which are needed in everyday life." (Ambrosio et al 2011). With other words: lack of a functional hand is practically not compatible with the normal daily living. Rehabilitation ideally targets all segments, but it is clearly unpractical to address 32 bones, 45 joints and 50 muscles of a human upper limb. Our simplified model develops along these three main systemic groups, possibly maintaining the full upper-limb kinematic range of motion for several activities of daily living (ADL) (Gates et al 2015).

The skeleton of the upper limb offers mechanical strength for the limb, but bones also might represent a potential structural basis for the robot, given the possibility of anchoring different parts of the device on the bony segments. The scapula and clavicle are having relatively low amplitude movements, and since such a device primarily has to be anchored on the thorax, these bones will not be targeted in an isotonic manner. Humeral movements have to be addressed by rehabilitation, given the high mobility of the segment. Radius and ulna are considered together, as one element, but capable of all the possible movements. Carpal and metacarpal bones might be considered as one functional unit, one targeted segment, since the role of individual movements between the mentioned bones are functionally negligible in case of gross disability. In opposition, finger movement recovery should be targeted individually. The simplified structure along with the in between joints of the shoulder, the elbow, the wrist and the little, distal joints of the fingers represents the target for rehabilitation, assuring a wide range of combined motion in the upper limb.

The muscular structure is responsible for the execution of the main possible movements of the mentioned joints. The shoulder normally can be flexed, extended, adducted, abducted and rotated inward and outward, the elbow flexed, extended and allows the pronation and supination of the forearm, the wrist flexed, extended, abducted, adducted, the distal joints flexed, extended, abducted, adducted. Movement complexity is achieved through a multitude of muscles with interweaved functions. Our model keeps just the main functional chain, which allows most of the mentioned movements, individual applied forces taking the place of several muscles combined function. These individual movements are proposed as the basic functional requirements (BFR) for each joint. When combined, the BFR are assuring the complexity of movements required for a good upper limb functioning. This conceptual model's graphical representation is shown in Graphic 1. of the Supplementary materials.

The presented model has to offer also numeric data regarding the maximum amplitude and strength of the movements. The intention is to build two open, continuously developed databases, describing our target population from the point of view of strength and range of motion, dynamic and mechanical characterization, in order to set a future robot to patient adapted motion ranges. The present work contains the format and preliminary data range for the considered motions. The development of the database for muscle strength is the subject of future research at the moment being in the "construction conceptualization" phase.

Materials and methods

Participants

The study design was approved by the Ethics Committee of the Municipal Clinical Hospital, Cluj-Napoca.

The study was performed on a group of 21 patients (11 females, 10 males), all hospitalized patients of the Municipal Clinical Hospital, Cluj-Napoca, the Neurology and Cardiology Departments. Each patient was informed prior to inclusion and signed an informed consent before the measurements.

Input measurements of the database should represent data from an age, gender and comorbidity-matched control group for the ischemic stroke population. Comorbidities are considered fixed, our target group having all the cerebral- and cardio-vascular risk factors of stroke patients, being in an age group which matches the age ranges of ischemic stroke. This age group is characterized also by high occurrence of chronic polyarthrotic diseases, influencing the range of motion. The age limits are quite wide, 40-85 and beyond, so this might represent a variable due to a higher stiffness of joints in elderly. Gender also might have an influence, flexibility of joints being higher in females.

Methods and equipment

The motion range measurements were made by using a standard goniometer, consisting of three parts: the body of the goniometer, forming a 0 to 360-degree full circle, the stationary arm, structurally a part of the body and the moving arm, attached to the centre by a screw, moving independently on the body.

First, the joint is postured in neutral position; the physiotherapist stabilizes the proximal segment using counter pressure to the resistance in order to eliminate substitute movements and to add validity to the test. Afterwards, the distal segment is gently moved by the physical therapist through the available range of motion until end-feel, then the joint returns to neutral position (Principles of Goniometry 2009).

Second, the therapist identifies and palpates the bony landmarks and aligns the goniometer first in the neutral position. Then the goniometer is removed, and the patient moves the joint through

Table 1. Pairwise test of angle difference, assessing the effect of laterality on the range of motion for each joint

Wilcoxon related sample test		p value
Shoulder_R_FL	Shoulder_L_FL	0.07
Shoulder_R_EXT	Shoulder_L_EXT	0.88
Shoulder_R_ABD	Shoulder_L_ABD	0.69
Shoulder_R_ADD	Shoulder_L_ADD	0.84
Elbow_R_FL	Elbow_L_FL	0.17
Elbow_R_PRON	Elbow_L_PRON	0.24
Elbow_R_SUP	Elbow_L_SUP	0.25
Rad_Carp_R_FL	Rad_Carp_L_FL	0.78
Rad_Carp_R_EXT	Rad_Carp_L_EXT	0.95
MCPh_R_FL	MCPh_L_FL	0.48
Ph1_Ph2_R_FL	Ph1_Ph2_L_FL	0.32
Ph2_Ph3_R_FL	Ph2_Ph3_L_FL	0.63

Table 2. Mean angles of the measured joints, the standard error of mean (S.E.) and standard deviation (S.D.)

Descriptive Statistics				
	N	Mean	S.E.	S.D.
Shoulder_FL	40	96.03	2.02	12.76
Shoulder_EXT	36	48.72	1.96	11.77
Shoulder_ABD	40	90.03	1.31	8.29
Shoulder_ADD	40	24.93	1.35	8.55
Elbow_FL	40	134.20	2.36	14.94
Elbow_PRON	40	79.43	2.21	14.00
Elbow_SUP	40	83.05	2.20	13.91
Rad_Carp_FL	36	59.75	2.52	15.12
Rad_Carp_EXT	36	45.14	2.28	13.69
MC_Ph_FL	42	73.29	2.79	18.07
Ph1_Ph2_FL	42	82.86	2.14	13.87
Ph2_Ph3_FL	42	54.36	2.95	19.14

the available range of motion. At the end of the stroke the goniometer is placed again, and the measurement registered.

The degree between the endpoints represents the range-of-motion (Principles of Goniometry 2009). The measurement is performed either in standing, or, if this is not possible, in sitting or lying position. The neutral position is with the upper limb next to the body in supine position (Goniometry Courses 2016). The measuring process is detailed in the supplementary materials. http://www.hvm.bioflux.com.ro/docs/Supplementary%20materials.pdf

Statistical analysis

The collected data was characterized using IBM SPSS Statistics version 20.0 software. First means, standard deviation and standard error of mean were calculated for the raw data. Different groups and categories were compared using different statistical methods, adjusted to sample size and type: the Wilcoxon non-parametric test for paired samples and the t-test for independent samples, threshold for significance being 0.05 for both tests.

Table 3. Mean angles of the investigated joints, in case of male and female subjects, and the t and p value of the applied T-test

	Mean		t-Test	
	Male	**Female**	**t**	**P**
Shoulder_FL	95.45	96.60	-0.28	0.78
Shoulder_EXT	46.67	50.77	-1.05	0.30
Shoulder_ABD	89.11	90.77	-0.63	0.54
Shoulder_ADD	25.85	24.00	0.68	0.50
Elbow_FL	133.35	135.05	-0.36	0.72
Elbow_PRON	73.67	84.14	-2.51	0.02
Elbow_SUP	83.22	82.91	0.07	0.95
Rad_Carp_FL	55.32	64.71	-1.93	0.06
Rad_Carp_EXT	39.95	50.94	-2.60	0.01
MC_Ph_FL	71.60	74.82	-0.57	0.57
Ph1_Ph2_FL	79.95	85.50	-1.31	0.20
Ph2_Ph3_FL	50.20	58.14	-1.36	0.18

Table 4. Mean age of the patient group. The value was used to form the under mean (< Mean) and over mean (> Mean) subgroups

Age	No of patients	Range	Minimum	Maximum	Mean	S.E.	S.D.
	21	40.00	43.00	83.00	61.86	2.57	11.79

Table 5. Mean angle differences according to age groups

	Mean angle		t-Test	
	< Mean (N)	**> Mean (N)**	**t**	**p**
Shoulder_FL	100.86 (22)	90.11 (18)	2.89	0.006
Shoulder_EXT	47.60 (20)	50.13 (16)	-0.63	0.53
Shoulder_ABD	93.27 (22)	86.06 (18)	3.01	0.005
Shoulder_ADD	26.18 (22)	23.39 (18)	1.03	0.31
Elbow_FL	135.45 (22)	132.67 (18)	0.58	0.56
Elbow_PRON	79.73 (22)	79.06 (18)	0.15	0.88
Elbow_SUP	85.64 (22)	79.89 (18)	1.31	0.20
Rad_Carp_FL	64.38 (21)	53.27 (15)	2.31	0.027
Rad_Carp_EXT	49.24 (21)	39.40 (15)	2.25	0.031
MC_Ph_FL	72.13 (24)	74.83 (18)	-0.48	0.64
Ph1_Ph2_FL	79.67 (24)	87.11 (18)	-1.77	0.09
Ph2_Ph3_FL	51.29 (24)	58.44 (18)	-1.21	0.24

Results

The mean ranges of motion angles for the selected joints were obtained by performing the descriptive characterization of the raw data. Since the laterality of a subject influences slightly the muscle size and this might have an impact on the development of the bone structure, tests were run to reveal if there are significant differences between the two sides, for the upper limb. At this point, being a pilot study with a reduced sample size, non-parametric evaluation was used: the Wilcoxon test for related-samples. First the sidewise dependence of shoulder flexion was compared (Graphic 2, Supplementary materials), and there were no significant differences between right and left, p=0.07. The next step was to perform the same analysis (Wilcoxon test) for the other joints and analysed movements. The returned p values are represented in Table 1, next to the analysed movement. No significance was registered.

Since there was no significance, all measured data, regardless of side, was used to calculate the mean angles and their standard error and standard deviation, the results are shown in Table 2.

After testing the effect of laterality on the range of motion, and obtaining the mean angle values, the following evaluation targeted the possible effect of gender on the same parameter. Again, all measured angles were used for a tested joint, offering a bigger sample size. The newly formed sample was then split in the males and female subject groups. Evaluation, given the sample size, was performed using the parametric t-test for independent samples. The p values show statistical significance for the forearm pronation and wrist extension, as Table 3 presents.

Then the evaluation targeted the effect of age on the measured angles. Here also the combined sample was used, permitting the use of parametric testing. The mean age was calculated, and two groups were formed, one consisting of the younger than mean subjects, the other from the older than mean. Age-dependent characterization of the sample is shown in Table 4.

The obtained angles are significantly lower for elderly people as in the Below Mean Group, an expected result at least for some joints. The differences are shown in Table 5.

Discussion

Most concepts for rehabilitation robots, either exoskeleton or end-effector type, are developed as an initiative of companies, the objective being approached from the viewpoint of producing a device to fulfil the demands of patients, physical therapists, neurologists (Perry et al 2007). Our proposal is similar in objectives, but the initiation comes from the other side: the physical therapist and physician. The proposal is starting from the limb's anatomy and the disabilities occurred as a part of the physiopathology of ischemic stroke. This approach allows a human tailored concept, which might be a feasible sketch for the design of a future rehabilitation robot. The continuous development of biomechanical – range of motion – and biodynamic – muscle strength – databases is offering the possibility to perform an evidence-based fine-tuning of the device during its development. The previously presented model might suffer technical-driven adjustments, to fully comply with the design requirements and constraints in the development of a rehabilitation robot. Presently the model has been developed for the upper limb, but the lower limb disability will also be addressed in future development. Strength of our model is the continuous link with numerical data gathered from a representative population for stroke, and characteristic for our geographical region.

The data presented in this paper focuses only on the range of motion. Even if the sample size is still low, the obtained angles are opposable, almost identical with the similar data from the literature (Normal Range of Motion Reference Values 2016). The sample size is continuously growing, constituting a dynamic database.

When compared with other authors, our study reveals also factors which might have an influence on the range of motion: age, sex, presence of comorbities (Pennestri et al 2007). This is really important, because a disabled limb has to be moved only to its physiological limits and a robot should be programmed accordingly. The same is true for the applied forces; these should not exceed normal muscle strength, otherwise, injury might happen. Our study already found a clear influence of age on range of motion: older patients are showing stiffer joints, lower motion amplitudes. This reveals a possible guideline for the robot – to either be tuned in an individualized manner for elderly, or to be programmed with this age group's mean values for all patients, these amplitudes being safe.

Another important finding is the importance of sex, women showing, at least for some of the joints, a higher range of motion, given the less robust skeletal structure and higher articular flexibility. This represents another possible guideline: all patients might use data obtained from males – safe for both categories – or individualization for the sexes.

Comorbidities were eliminated as an influencing factor when the database was built, by fixing their presence for the control group as an inclusion criterion – random presence (assured by the similar age) of cardio-, cerebral-vascular and motor system diseases. This approach is also different: not using healthy individuals for control.

Conclusion

This work is a part of an ongoing activity for developing robotic rehabilitation means along with the development of a database for biodynamic measurements, representing a novel approach for the conceptualization and future development of a human-tailored fine-tuned robot for physical therapy.

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Authors

- Kinga A. Major, Cluj County Emergency Hospital, Neurosurgery Clinic, ICU II, 43 Babes Street, 400012, Cluj-Napoca, Cluj, Romania, EU, email: majorkinga@yahoo.com
- Zoltán Zs. Major, Neurology Department, Municipal Clinical Hospital Cluj-Napoca, 400139, Tabacarilor Street 11., Cluj-Napoca, Cluj, Romania, EU or Department of Functional Sciences, “Iuliu Hatieganu” University of Medicine and Pharmacy, 23 Gheorghe Marinescu Street, 400337, Cluj-Napoca, Cluj, Romania, EU, email: zoltan.major@eeg-emg.ro
- Giuseppe Carbone, Laboratory of Robotics and Mechatronics, DiCEM, University of Cassino and South Latium, 43 G. Di Biasio Street, 03043, Cassino, Italy, EU, email: carbone@unicas.it
- Adrian Pîslă, Research Center for Industrial Robots Simulation and Testing, CESTER, Technical University of Cluj-Napoca, Romania 103-105 Bvd. Muncii Street, 400641, Cluj-Napoca, Cluj, Romania, EU, email: adrian.pisla@muri.utcluj.ro
- Călin L. Vaida, Research Center for Industrial Robots Simulation and Testing, CESTER, Technical University of Cluj-Napoca, Romania 103-105 Bvd. Muncii Street, 400641, Cluj-Napoca, Cluj, Romania, EU, email: calin.vaida@mep.utcluj.ro
- Bogdan Gherman, Research Center for Industrial Robots Simulation and Testing, CESTER, Technical University of Cluj-Napoca, Romania 103-105 Bvd. Muncii Street, 400641, Cluj-Napoca, Cluj, Romania, EU, email: bogdan.gherman@mep.utcluj.ro
- Doina L. Pîslă, Research Center for Industrial Robots Simulation and Testing, CESTER, Technical University of Cluj-Napoca, Romania 103-105 Bvd. Muncii Street, 400641, Cluj-Napoca, Cluj, Romania, EU, email: doina.pisla@mep.utcluj.ro

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