4th International Conference on Production Economics
and Project Evaluation
ICOPEV 2018, Guimarães, Portugal

LITERATURE REVIEW AND ANALYSIS OF WRIST REHABILITATION DEVICES

Ana Oliveira,[1] Eurico Seabra[1], Luís F. Silva[1*] and Hélder Puga[1]

[1] Department of Mechanical Engineering, University of Minho, Portugal

* Corresponding author: lffsilva@dem.uminho.pt, University of Minho, Guimarães, 4800-058, Portugal

KEYWORDS
Wrist, Medical device, Rehabilitation

ABSTRACT

The wrist is a very important joint of the human body, involved in several basic activities. When the wrist is injured, it causes a significant disturbance in the quality of life. Therefore, patients have difficulty to perform some tasks. The main devices used in rehabilitation clinics and hospitals are very simple and often directed to only one type of movement, not providing the complete rehabilitation of the wrist. In order to solve this problem, new devices, therapies and systems for wrist rehabilitation have been developed. These mainly consist of virtual reality therapies, exoskeletons, gloves and vibratory therapies. The performed analysis showed that an ideal wrist rehabilitation device does not exist, but many devices complement each other and provide a good therapy. Recently it has been indicated vibratory therapies to aid the rehabilitation of traumatic injuries. These have shown very positive effects, even in the wrist rehabilitation. In future developments, this characteristic should be implemented, through the development of a portable vibratory device with frequencies and magnitudes of vibration appropriate to the human body.

INTRODUCTION

Patients with wrist injuries have difficulty to perform many daily tasks, such as open and close a door, go to the bathroom, or even to dress or handle on cutlery.

The process of wrist rehabilitation is based on physiotherapy sessions that requires physical interactions between patients and therapists (Aabdallah et al., 2016). In this process three rehabilitation components are incorporated, namely muscle strengthening, joint amplitude gain and pain relief. However, the success of wrist rehabilitation therapy is dependent on the therapists available and the exercises that patients perform outside the physiotherapy sessions (Bartlett et al., 2015). In these, among all the different methodologies used, it is quite common the use of rehabilitation devices, that aim to increase the joint mobility of patients, easing the work of physiotherapists.

The main devices used in rehabilitation clinics are very simple and consist on the use of mechanical springs, dumbbells, balls, bars, pedals, finger ladders, finger nets and on the adoption of many other rehabilitation procedures that depend on the creativity of each professional. In this way, cloths with buttons, door handles and many other everyday things are currently used. These devices are very simple, affordable and easily transportable. However, as a result of its simplicity, the current wrist rehabilitation devices are often directed to only one type of movement. Several devices are therefore required to complete the rehabilitation process. In fact, most of the devices are only aimed at strengthening the grip movement, not taking into account the flexion-extension, radial-ulnar deviation and pronation-supination movements. In addition, current devices only focus on muscle strengthening and do not have any mechanisms for joint amplitude gain and pain relief.

Thus, it is necessary to find forms of rehabilitation that act not only on the three components of the wrist rehabilitation process but also offer the possibility of transportation to any place (portable device). In this way, the rehabilitation process is not restricted to rehabilitation clinics and can be continued anywhere. However, the simplicity of the devices must be maintained to the user, avoiding therefore its rejection.

In order to resolve the problems of marketed devices and to meet the mentioned requirements, new devices, systems and therapies have been developed (Bartlett et al., 2015; Brewin et al., 2017; Hsieh et al., 2016). These are very different from the devices used in rehabilitation clinics and hospitals.

In this paper, we have performed a literature review and an analysis of the devices that have been designed and developed for this purpose. Some positive and negative aspects are highlighted, performing a comparison with the devices that are currently used in hospitals and rehabilitation clinics.

METHODOLOGY

The new developed devices herein presented were obtained through the research of relevant literature using databases such as Google Scholar, PubMed and Web of Science, applying the following keywords: wrist, wrist rehabilitation, wrist device, wrist robot, upper limb rehabilitation, forearm rehabilitation, arm rehabilitation, hand rehabilitation, fingers rehabilitation, stroke, and hemiparesis. It must also be emphasized that only the papers published from 2005 have been considered in this study.

RESULTS

This section is intended for the study of wrist rehabilitation devices. Therefore all the new devices, systems or therapies that have been designed and developed since 2005 are presented in this section.
Based on this research it is possible verify that there are many devices, systems or therapies to provide wrist rehabilitation. Despite its great diversity, there are some classes that stand out, such as virtual reality therapies (Hsieh et al., 2016; Tsoupikova et al., 2015), exoskeletons, gloves (Bartlett et al., 2015; Polygerinos et al., 2015; Yap et al., 2015) and vibratory therapies (Brewin et al., 2017).
The virtual reality therapies (see Figure 1) are very encouraging because they allow the simulation of tasks and daily activities, causing patients to perform these tasks and view them virtually (Hsieh et al., 2016; Tsoupikova et al., 2015). However, they do not allow the continuation of the therapy outside the rehabilitation environment, reducing therefore the frequency of treatment.

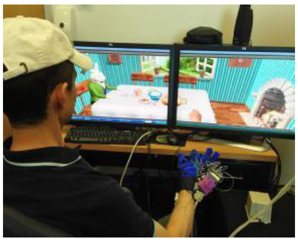

Figure 1: Example of a Virtual Reality Therapy (Tsoupikova et al., 2015)

The BloBo Bluetooth Ball is a new system for wrist rehabilitation that fits in this type of therapy (Hsieh et al., 2016). It enables a precise and diversified rehabilitation. To start the rehabilitation, the ball must be tossed into the air or a shaking-type of movement must be inflicted to the ball; these movements of the ball are detected by its sensors. This is a computer based-control system and the rehabilitation procedure is carried out with a computer game or a song. The patient must play the game or move himself to the sound of the music, performing the rehabilitation exercises (flexion, extension, radial deviation, ulnar deviation and grasping movements). This system also enables the storage of the rehabilitation performance data of the patients. The level of difficulty of the exercises is adapted to the state/condition of each patient.
There are other authors who have also developed virtual reality systems. Tsoupikova et al. (2015) proposed a system that enables the rehabilitation of the hand and arm of people who have suffered a stroke, Figure 1. This device has a glove to aid in the performance of repetitive tasks and according to the published results an increase of the patients progress have been observed.
CRAMER is another type of virtual reality (Spencer et al., 2008). The therapy consists in playing computer-based exercise games, allowing flexion, extension, radial deviation, ulnar deviation, pronation and supination movements. For this purpose, the remote for Nintendo's Wii was integrated into the handle of the robot.
Another therapy involving virtual reality is the HWARD (Takahashi et al., 2007). This system is pneumatically actuated, that assists the hand in grasp and in release movements. For therapy, the hand is secured to the robot mechanism through three soft straps, and the forearm is placed inside of a padded splint on the surface of platform. The palmar hand is unobstructed for placement of real objects into a grasping hand. The HWARD has joint angle sensors that measure the joints of the robot. Therefore, hand movements are allowed in virtual reality in real time, where the patient's hand controls a virtual hand on the computer screen. The therapy produced significant behavioral gains in patients with chronic moderate motor deficits following stroke.
Krebs et al. (2007) also developed a similar system that allows all wrist and forearm movements, providing continuous passive motion, strength, sensory, and sensorimotor training for the wrist.
Other therapy of this kind was also proposed by Colombo et al. (2007) that only allows the wrist flexion-extension movement through rehab games. This therapy allows to adapt the degree of difficulty for each patient, selecting appropriate motor tasks to their disability. Besides that, a periodic review of the patient performance motivates them to continue rehabilitation (offers visual feedback of performance scores and praises patients for their efforts). A reduction of the motor deficit and significant improvements in the clinical scales and the parameters measured by the robot were verified.
Although not properly considered as a virtual reality therapy, the wrist rehabilitation methodologies have also arrived to smartphone applications. The HandRehab is a smartphone application that allows the rehabilitation of the wrist anywhere, Figure 2 (Matera et al., 2016) and it uses the GPS and the accelerometer of the smartphone. The smartphone is attached to the hand through a splint and the application measures the movement performed by the hand of the patient through the accelerometer (flexion, extension, radial deviation, ulnar deviation, pronation and supination) and allows the storage of the rehabilitation data. In this therapy, patients performed maximal passive motion with assistant of contralateral uninjured side. Patient satisfaction was consistently high as well as adherence to therapy and wrist movement ranges.

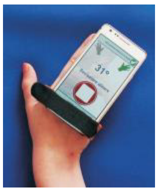

Figure 2: HandRehab (Matera et al., 2016)

In turn, the gloves and exoskeletons (Figure 3) are more directed to the rehabilitation of the fingers, not exerting a great therapeutic component in the wrist (Bartlett et al., 2015; Polygerinos et al., 2015; Yap et al., 2015). Usually, an exoskeleton is found around the hand, guiding the fingers joints in the desired trajectories.

Figure 3: Example of a Glove (Bartlett et al., 2015)

In this category was also developed a workstation based on cybernetic gloves and strength training devices for hand rehabilitation (Chen et al., 2015). This system also enables the recording of the patients information. With the use of the gloves it is possible to perceive the degree of limitation of the patient and to prescribe an appropriate therapy. For the therapy, the force training devices are used.
The ExoGlove was proposed by Yap et al. (2015) and it consists of a soft wearable exoskeleton with a glove embedded and velcro straps. This device has pneumatic actuators of variable stiffness which allow the assistance and rehabilitation of the hand. Due to the variable stiffness of the actuators in different locations, it allows them to adjust to the profile of the finger during the actuation. The device has the assistive mode (daily activities - grasping, pinching) and the rehabilitation mode (repetitive tasks - continuous passive movements). Furthermore, can be customized for different dimensions of the hand. Through a motion capture system and force sensors it was possible to characterize the device in range of motion and force. The results obtained demonstrated an acceptable range of motion and sufficient strength to perform different tasks, being able to guide the fingers and create movements such as hand grasping and pinching.
Other authors also focused their study on a pneumatic glove (Polygerinos et al., 2013). This glove presents soft actuators composed by elastomeric materials with integrated channels that work as pneumatic networks. This device allows flexion of the fingers of the hand and the glove features an open palm design.
Polygerinos et al. (2015) developed another open palm design glove. However, this one does not uses pneumatic actuators, but hydraulic actuators. This glove is also capable to replicate the movements of the fingers of the hand.
A soft robotic orthosis pneumatically assisted for patients who have suffered a stroke was also proposed by Bartlett et al. (2015), Figure 3. This orthosis is able to assist patients in the flexion-extension and radial-ulnar deviation movements of the wrist and pronation-supination of the forearm. According to the patient's condition, different levels of assistance can be programmed on the robotic orthosis.
The RiceWrist is a haptic exoskeleton device which allows the flexion-extension and radial-ulnar deviation of the wrist and pronation-supination of the forearm (Gupta et al., 2008). This device allows the measurement of the human joint angles and provides a kinesthetic feedback for each joint. Similar to virtual reality therapies, the RiceWrist is also targeted to patients who have suffered a stroke.
It is often difficult to distinguish between exoskeletons and wrist robots. More recently was developed a wrist robot that develops the flexion-extension and radial-ulnar deviation movements of the wrist (Aabdallah et al., 2016). This robot is able to detect the patient's degree of pain using the electromyography signal. Due to its characteristics, this robotic device is capable to determine the desired angle, real-time velocity and to storage all the procedure information.
Moreover, Takaiwa and Noritsugu (2005) proposed a mechanical device which has a pneumatic manipulator of multiple degrees of freedom that, grasping the handle, allows complex movements of the wrist (see Figure 4). Thus, flexion-extension and radial-ulnar deviation movements of the wrist can be performed, along with pronation-supination of the forearm. Furthermore, this device includes an impedance control system that allows for various modes of rehabilitation. Through the adjustment of some parameters, it is possible to implement several exercises.

Figure 4: Pneumatic Parallel Manipulator (Takaiwa and Noritsugu, 2005)

Rashedi et al. (2009) proposed a robotic device for the rehabilitation of patients who have suffered stroke. This device is also capable of providing flexion-extension movements of the wrist and pronation-supination of the forearm, and, besides that, it can operate in passive, active and active bimanual mode. The passive mode allows the adjustment of the speed and range of motion. The active mode allows an independent movement, with the presence of an adjustable resistance. The active bimanual mode allows the more functional member to assist the weakened limb in performing the movements through symmetrical exercises.

Song et al. (2007) also studied the effect of a robotic system for the rehabilitation of patients who suffered stroke. However, this is myoelectrically controlled. The system is capable of providing the flexion-extension movement of the wrist. In this system, electromyography signals of the radial carpal flexor and radial carpal extensor are used to detect the patient's effort. Due to this reason, it is possible to control the mechanical assistance of the system.

In recent years, vibratory therapies have been studied and have demonstrated a number of benefits, such as improvements in patients with multiple sclerosis, recovery of muscle strength and function, prevent bone loss and accelerate the healing of the bone without inhibiting the healing of the ligament in traumatic lesions (Bily et al., 2016; Camerota et al., 2017; Huang et al., 2017; Pamukoff et al., 2016; Thompson et al., 2015). Brewin et al. (2017) showed that the vibration can help in the rehabilitation process after the occurrence of a traumatic wrist injury. However, they did not use a device specifically designed for the wrist joint, using an air sander and a vibroplate (see Figure 5).

Figure 5: Wrist Rehabilitation using a Sander Air, Left Panel, and a Vibroplate, Right Panel (Brewin et al., 2017)

DISCUSSION

After the analysis presented in the previous section, it is verified that there is a difference of complexity between the devices used in rehabilitation clinics (current and commercialized devices) and those that have been developed recently (new devices, therapies and systems developed and/or under development). Some advantages and disadvantages can be pointed out to these devices.

In general, recent developments in this area present a superior complexity and consequently their price may increase when compared to current devices which present a low cost value as a result of their simplicity. Furthermore, these devices are not portable, unlike the ones used in rehabilitation clinics and hospitals. Therefore the rehabilitation process can be restricted to the places where they are located and can not be continued at home or elsewhere. In addition to allowing therapies more adapted to each patient, these devices are capable to perform the rehabilitation process in a more controlled way (there is supervision avoiding inappropriate exercises), with greater frequency and with visualization of the patient's progression. Thus, the rehabilitation exercises are adapted to each patient. These devices do not require a continuous monitoring of the physical therapist because the data can be stored for future reference. This is a consequence of the evolution of technology and the search for solutions that best fit the modern lifestyle. One negative aspect is its characteristics and operating modes that can be confusing to the user, unlike current devices that do not require great skills for their use. This particular reason may cause the rejection of the device. Furthermore, they normally do not allow only one type of movement, but a complete set of movements of the wrist and forearm. In turn, current devices typically allow only one type of movement, meaning that several devices are required to complete all the movements needed to the rehabilitation process. In fact, most of the current devices are only aimed at strengthening the grip movement, leaving aside the flexion-extension and radial-ulnar deviation movements of the wrist and even pronation-supination of the forearm. In addition, current devices only focus on muscle strengthening and do not have mechanisms for joint amplitude gain. Therefore another positive aspect of recent devices is their "mixed" operation. On the other hand, in current devices the patient provides the force to move or grasp the device (passive operation); at early stages of rehabilitation however the patient may not be able to work with the device and current practice tell us that both active and mixed devices are missing from present rehabilitation procedures of the wrist.

The virtual realities strategies stand out as one of the developments undertaken in this area (Hsieh et al., 2016; Tsoupikova et al., 2015). The virtual realities allow animated and less monotonous therapies, often through games and songs (Hsieh et al., 2016; Spencer et al., 2008). This fact motivates patients, which is a crucial aspect of the rehabilitation process. These consist in therapies more appropriate to each type of patient and to their rehabilitation process. They are directed to daily basic activities and patients do not have so many difficulties, which is an important factor to increase their motivation. Without noticing, patients integrate an environment that encourages them to perform basic tasks of their everyday life. Many times, the degree of complexity of the exercises is gradually increased or adapted to the clinical condition of each patient (Colombo et al., 2007; Hsieh et al., 2016). In addition, these therapies allow real-time visualization of the exercises and if they are being performed correctly or not. However, in most cases it is not allowed to continue the therapy at home. An important feature of these studies is the focus on people who have suffered stroke (Tsoupikova et al., 2015) and typically these systems are not used to rehabilitate patients with fractures and tendinitis, which still remains a problem.

The CRAMER is a virtual reality therapy that uses the remote for Nintendo's Wii in the rehabilitation process, making this therapy fun and familiar to its users (Spencer et al., 2008). The same applies to the smartphone application developed by Matera et al. (2016). The HandRehab does not require great skills and fits into the modern lifestyle. Nowadays, smartphone applications are quite common and very promising. Combining this aspect with the power of rehabilitation (to be carried out anywhere and anytime) this is an extraordinary feature to the end user. Furthermore, the data storage allows visualization of the patient's progress, not requiring the physical interaction between the patient and the therapist, which was also an interesting aspect considered by Hsieh et al. (2016).

The exoskeletons and the gloves are another class of devices that have been extensively developed for the rehabilitation of the fingers (Bartlett et al., 2015; Chen et al., 2015; Polygerinos et al., 2015; Yap et al., 2015). Although they may help, these devices are not mainly targeted for wrist therapy. In addition, they are uncomfortable due to their rigid components (motor and actuator), inducing high stresses at the exoskeleton support connectors and the hand and preventing the natural movement of the joints. This restricts the degrees of freedom not triggered (Yap et al., 2015). Unlike virtual reality therapies, the exercises can be monotonous and demotivate the patient. Moreover, they are generally not portable, restricting rehabilitation just to clinics. Nevertheless there are recently developed portable and lightweight devices, such as the soft wearable device proposed by Bartlett et al. (2015), which is capable to be used outside rehabilitation clinics. This is a positive aspect that contrasts with most of the devices (large and heavy) that have been developed. Furthermore, it allows the programming of different service levels, increasing the patient's progress. Likewise, Chen et al. (2015) and Rashedi et al. (2009) also studied therapies addressed to each patient.

Aabdallah et al. (2016) and Chen et al. (2015) proposed therapies and systems that also allow the recording of information about the patients and their rehabilitation process. This fact is extremely important these days. When the patient goes to a rehabilitation clinic, sometimes his therapist may not be working or may be attendeing another patient. In these situations the patient may have to be treated by another specialist who does not know his clinical condition or his stage of rehabilitation. By recording the information about each rehabilitation session, the therapist can easily know the type of therapy that should be applied to the patient, avoiding therefore inappropriate therapies.

There is a developed robot that presents an interesting feature that has not been included in other devices, which concerns with the pain felt by the patient (Aabdallah et al., 2016). In fact, the pain causes the patient not to move the joint or to move it with a high degree of suffering.

A pneumatic manipulator developed by Takaiwa and Noritsugu (2005) allows a complex movement of three degrees of freedom. When wrist mobilization is needed in some task, conjugated movements are usually performed, being rare the movements of only one degree of freedom. According to these authors, this system provides a movement of the wrist quite similar to the one developed in normal mobility conditions.

The robotic device proposed by Rashedi et al. (2009) presents a fundamental characteristic for the success of rehabilitation, that is its ability to operate in three rehabilitation modes as mentioned previously. This device can accompany the patient during all his rehabilitation process.

The myoelectrically controlled robotic system as proposed by Song et al. (2007) allows the control of the mechanical assistance of the system according to the capacity of the patient. In addition, it allows to detect the patient's effort, which is a positive and innovative aspect. However, it only allows one type of movement, such as the virtual reality therapy proposed by Colombo et al. (2007), being its performance similar to the one observed in current devices.

In the same way as virtual reality therapies, also gloves and exoskeletons are very directed to stroke patients (Bartlett et al., 2015; Gupta et al., 2008; Rashedi et al., 2009; Song et al., 2007).

According to Brewin et al. (2017), vibratory therapies have shown a high therapeutic potential, acting in all components of rehabilitation, such as muscle strengthening, joint amplitude gain and pain relief. Furthermore, these therapies have demonstrated a huge number of benefits in the physiology of the human body, such as improvements in patients with multiple sclerosis, recovery of muscle strength and function, prevent bone loss and accelerate the healing of the bone without inhibiting the healing of the ligament in traumatic lesions (Bily et al., 2016; Camerota et al., 2017; Huang et al., 2017; Pamukoff et al., 2016; Thompson et al., 2015). This will be a promising and innovative rehabilitation therapy that will help not only stroke patients to regain their functions. Besides that, the risk of wrong exercises without supervision is low. However, it was observed in this analysis that there are no vibratory devices directly addressed to the rehabilitation of the wrist. Therefore, the development of such portable devices is very important and a special attention should be addressed to the frequencies and magnitudes of vibration, as well as to its modes of vibration and transmission.

CONCLUSIONS AND FURTHER RESEARCH

According to the analysis herein presented, it is possible to concluded that there is no ideal device for the wrist rehabilitation, but many devices complement each other and provide a good therapy procedure.

Recent developments point to more attractive therapies, more appropriate to each type of patient and to their rehabilitation process, undertaking similar tasks to the ones that the human being needs to perform. Besides that, these require a reduced interaction between the patient and therapist. However, they are generally proposed to rehabilitate patients with neurological injuries, such as stroke. In this way, other types of pathologies have been forgotten, as is the case of bone lesions and tendinous origin.

Recently it has been indicated vibratory therapies to aid the rehabilitation of traumatic injuries. These have shown very positive effects and benefits in the three components of wrist rehabilitation.

In future developments, this characteristic should be implemented, through the development of a portable vibratory device with frequencies and magnitudes of vibration appropriate to the human body and so that the rehabilitation of the wrist is no longer confined to the rehabilitation clinics.

REFERENCES

Aabdallah, I. B.; Y. Bouteraa; and C. Rekik. 2016. "Design of smart robot for wrist rehabilitation." *International Journal on Smart Sensing and Intelligent Systems* 9, No.2 (Jun), 1029-1053.

Bartlett, N. W.; V. Lyau; W. A. Raiford; D. Holland; J. B. Gafford; T. D. Ellis; and C. J. Walsh. 2015. "A Soft Robotic Orthosis for Wrist Rehabilitation." *Journal of Medical Devices* 9, No.3 (Sep), 030918.

Bily, W.; C. Franz; L. Trimmel; S. Loefler; J. Cvecka; S. Zampieri; W. Kasche; N. Sarabon; P. Zenz; and H. Kern. 2016. Effects of leg-press training with moderate vibration on muscle strength, pain, and function after total knee arthroplasty: a randomized controlled trial. *Archives of physical medicine and rehabilitation* 97, No.6 (Jun), 857-865.

Brewin, M. P.; C. J. Bexon; and S. C. Tucker. 2017. A case report on the use of vibration to improve soft tissue extensibility after major trauma. *Journal of Hand Therapy* 30, No.3 (Nov), 367-371.

Camerota, F.; C. Celletti; E. Di Sipio; C. De Fino; C. Simbolotti; M. Germanotta; M. Mirabella; L. Padua; V. Nociti. 2017. Focal muscle vibration, an effective rehabilitative approach in severe gait impairment due to multiple sclerosis. *Journal of the neurological sciences* 372, 33-39.

Chen H.; H. Ou; and H. Chen. 2015. "A Method for Rehabilitation of Hand Dysfunction by Cyber Glove." *5th International Conference on Advanced Engineering Materials and Technology.* 393-396.

Colombo, R.; F. Pisano; A. Mazzone; C. Delconte; S. Micera; M. C. Carrozza; P. Dario; and G. Minuco. 2007. "Design strategies to improve patient motivation during robot-aided rehabilitation." *Journal of neuroengineering and rehabilitation* 4, No.1 (Feb), 3.

Gupta, A.; M. K. O'Malley; V. Patoglu; and C. Burgar. 2008. "Design, control and performance of RiceWrist: a force feedback wrist exoskeleton for rehabilitation and training." *The International Journal of Robotics Research* 27, No.2 (Apr), 233-251.

Hsieh, W. M.; Y. S. Hwang; S. C. Chen; S. Y. Tan; C. C. Chen; Y. L. Chen. 2016. "Application of the Blobo bluetooth ball in wrist rehabilitation training." *Journal of physical therapy science* 28, No.1 (Oct), 27-32.

Huang, Y.; H. Luan; L. Sun; J. Bi; Y. Wang; and Y. Fan. 2017. Local vibration enhanced the efficacy of passive exercise on mitigating bone loss in hindlimb unloading rats. *Acta Astronautica* 137, (Aug), 373-381.

Krebs, H. I.; B. T. Volpe; D. Williams; J. Celestino; S. K. Charles; D. Lynch; and N. Hogan. 2007. "Robot-aided neurorehabilitation: a robot for wrist rehabilitation." *IEEE transactions on neural systems and rehabilitation engineering* 15, No.3 (Sep), 327-335.

Matera, G.; C. Boonyasirikool; R. Saggini; A. Pozzi; and L. Pegoli. 2016. "The new smartphone application for wrist rehabilitation." *The Journal of Hand Surgery (Asian-Pacific Volume)* 21, No.1 (Nov), 2-7.

Pamukoff, D. N.; B. Pietrosimone; M. D. Lewek; E. D. Ryan; P. S. Weinhold; D. R. Lee; and J. T. Blackburn. 2016. Whole-body and local muscle vibration immediately improve quadriceps function in individuals with anterior cruciate ligament reconstruction. *Archives of physical medicine and rehabilitation* 97, No.7 (Jul), 1121-1129.

Polygerinos, P.; S. Lyne; Z. Wang; L. F. Nicolini; B. Mosadegh; G. M. Whitesides; and C. J. Walsh. 2013. "Towards a soft pneumatic glove for hand rehabilitation." *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems* (Tokyo, Japan, Nov.3-7). IEEE, 1512-1517.

Polygerinos, P.; Z. Wang; K. C. Galloway; R. J. Wood; and C. J. Walsh. 2015. "Soft robotic glove for combined assistance and at-home rehabilitation." *Robotics and Autonomous Systems* 73, (Nov), 135-143.

Rashedi, E.; A. Mirbagheri; B. Taheri; F. Farahmand; G. R. Vossoughi; and M. Parnianpour. 2009. "Design and development of a hand robotic rehabilitation device for post stroke patients." *31st Annual International Conference of the IEEE Engineering in Medicine and Biology Society* (Minneapolis, Minnesota, USA, Sep.2-6). IEEE, 5026-5029.

Song, R.; K. Y. Tong; X. L. Hu; and X. J. Zheng. 2007. "Myoelectrically controlled robotic system that provide voluntary mechanical help for persons after stroke." *Proceedings of the 2007 IEEE 10th International Conference on Rehabilitation Robotics* (Noordwijk, The Netherlands, Jun.12-15). IEEE, 246-249.

Spencer, S. J.; J. Klein; K. Minakata; V. Le; J. E. Bobrow; and D. J. Reinkensmeyer. 2008. "A low cost parallel robot and trajectory optimization method for wrist and forearm rehabilitation using the Wii." *Proceedings of the 2nd Biennial IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics* (Scottsdale, AZ, USA, Oct.19-22). IEEE, 869-874.

Takahashi, C. D.; L. Der-Yeghiaian; V. Le; R. R. Motiwala; and S. C. Cramer. 2007. "Robot-based hand motor therapy after stroke." *Brain* 131, No.2 (Feb), 425-437.

Takaiwa, M. and T. Noritsugu. 2005. "Development of wrist rehabilitation equipment using pneumatic parallel manipulator." *Proceedings of the 2005 IEEE International Conference on Robotics and Automation* (Barcelona, Spain, Apr.18-22). IEEE, 2302-2307.

Thompson, W. R.; B. V. Keller; M. L. Davis; L. E. Dahners; and P. S. Weinhold. 2015. Low-Magnitude, high-frequency vibration fails to accelerate ligament healing but stimulates collagen synthesis in the Achilles Tendon. *Orthopaedic journal of sports medicine* 3, No.5 (May), 2325967115585783.

Tsoupikova, D.; N. S. Stoykov; M. Corrigan; K. Thielbar; R. Vick; Y. Li; Triandafilou K.; Preuss F.; and D. Kamper. 2015. "Virtual immersion for post-stroke hand rehabilitation therapy." *Annals of biomedical engineering* 43, No.2 (Feb), 467-477.

Yap, H. K.; J. H. Lim; F. Nasrallah; J.C. Goh; and R. C. Yeow. 2015. "A soft exoskeleton for hand assistive and rehabilitation application using pneumatic actuators with variable stiffness." *2015 IEEE International Conference on Robotics and Automation* (Seattle, Washington, May 26-30). IEEE, 4967-4972.