Model based Open-Loop Posture Control of a Parallel Ankle Assessment and Rehabilitation Robot*

Mingming Zhang, *Student Member, IEEE,* Bo Sheng, T. Claire Davies, Wei Meng, Sheng Q. Xie*, *Senior Member, IEEE*

***Abstract*— Ankle injuries are very common in daily life out of musculoskeletal or neurological reasons. Traditional ankle therapy usually requires cooperative and intensive efforts from therapists and patients. Robot-assisted ankle rehabilitation techniques have been actively researched in the past few decades. However, limitations exist such as inaccurate robotic design, limited robotic range of motion (ROM) and torque generation capability, or lack of measurement of the interaction between robots and patients. This study developed a novel ankle assessment and rehabilitation robot (AARR) that could perform a three-dimensional robotic training with real-time ankle assessment. A preliminary test was conducted on a healthy subject using a model based open-loop controller. Results show that the robotic training is continuous and stable although the trajectory tracking accuracy is not high. It is concluded that this robotic design has potential in clinical applications for ankle rehabilitation. This model based open-loop controller could provide stable robotic training and suitable for low precision tracking requirement. Future work will focus on realizing advanced training modes and the improvement of trajectory tracking accuracy.**

I. INTRODUCTION

The human ankle joint is a complex bony structure [1], which greatly affects lower extremity function [2]. The incidence of ankle injuries is high due to extensive exposure to large loads (can reach up to several times of the body weight). Ankle sprains are very common in sports and daily life and could be caused by overstretching or tearing of ankle ligaments [1]. An estimated 23,000 cases occurred per day in the United States [3]. In New Zealand, the Accident Compensation Corporation received over 230,000 new claims and 278,000 ongoing claims with respect to ankle injuries from July 2009 to June 2014 [4]. Neurologic injuries such as stroke, cerebral palsy and traumatic brain could also lead to ankle injuries. Drop foot is a common impairment following stroke. In New Zealand, there are an estimated 60,000 stroke survivors.

Conventional ankle rehabilitation treatments usually require cooperative and intensive efforts from therapists and patients over prolonged sessions [5]. Robot-aided rehabilitation technology has been actively developed in the past few decades and allows the transformation of rehabilitation clinics from labor-intensive operations to technology-assisted operations as well as a rich stream of data that can facilitate patient diagnosis, customization of the therapy, and maintenance of patient records (at the clinic and at home) [6]. The effectiveness of existing ankle rehabilitation devices has been systematically reviewed by Zhang, et al. [7] and clinical trials have demonstrated their positive effects on reducing ankle impairment caused by either musculoskeletal or neurological reasons.

Existing robot-assisted ankle rehabilitation devices could be classified into wearable robots aiming at improving ankle performance during gait and platform based robots focusing solely on improvement of ankle performance [7]. Although platform based parallel robots have been considered suitable for ankle rehabilitation due to the multi-degrees of freedom (DOFs) and large torque generation capacity characteristics, few has been well developed and validated for ankle assessment and rehabilitation. A typical instance is the "Rutgers Ankle" based on a Stewart-Gough platform with six DOFs powered by double-acting pneumatic cylinders [8]. This system has been extensively researched and shown potential for clinical applications. However, in this system the ankle joint does not remain stationary during the robotic training, which could cause difficulty in controlling the robot and require synergic movement from the patients' lower limbs. Some other parallel robots have also been developed for ankle rehabilitation [9-11]. However, most existing platform based ankle robots have a similar mechanical structure wherein the moving platform is actuated from the bottom and its rotational center does not coincide with the ankle joint. This could lead to inaccurate rehabilitation motions.

Our lab recently developed an ankle rehabilitation robot that could ensure the ankle joint remains stationary during robot-assisted therapy [12]. Although this robot showed potential in terms of superior structure and lightweight pneumatic muscle actuators, as well as good tracking accuracy of the fuzzy-logic based control strategy, some limitations (limited torque generation capability and no measurement of real-time patient-robot interaction) still exist and impede its clinical applications.

*Resrach supported by University of Auckland, under Faculty of Engineering Research Development Fund 3625057 (Physical Robot-Human Interaction for Performance-Based Progressive Robot-Assisted Therapy) and China Sponsorship Council.

M. M. Zhang is with the Department of Mechanical Engineering, University of Auckland, Auckland 1142, New Zealand (e-mail: mzha130@aucklanduni.ac.nz).

B. Sheng is with the Department of Mechanical Engineering, University of Auckland, Auckland 1142, New Zealand (e-mail: bshe687@aucklanduni.ac.nz).

W. Meng is with the Department of Mechanical Engineering, University of Auckland, Auckland 1142, New Zealand (e-mail: wmen386@aucklanduni.ac.nz).

T. C. Davies is with the Department of Mechanical Engineering, University of Auckland, Auckland 1142, New Zealand (e-mail: c.davies@auckland.ac.nz).

*S. Q. Xie is with the Department of Mechanical Engineering, University of Auckland, Auckland 1142, New Zealand (correspondence e-mail: s.xie@auckland.ac.nz).

This research involved the development of a novel AARR based on the previous prototype. This new robot is light in weight and compatible with ankle motions. The use of Festo Fludic muscles (FFMs) allows large robotic torque generation capability. This robotic design also allows the realization of advanced training strategies by the integration of real-time ankle assessment. However, an open-loop posture control approach was proposed to operate safely as a preliminary test. This paper describes the design and the model based open-loop controller. Experiments on a healthy subject were carried out and results were analyzed.

II. ANKLE ASSESSMENT AND REHABILITATION ROBOT

A. Mechanical Design

This AARR is actuated by four parallel actuators for three rotational DOFs. These three DOFs respectively represent ankle's natural motions in dorsiflexion/plantarflexion, inversion/eversion and abduction/adduction. This new robotic design was proposed based on an existing ankle prototype developed in Mechatronics Lab of The University of Auckland [12]. Two main things have been significantly improved: one is the use of FFMs (FESTO DMSP-20-400N-RM-CM) and the other is the integration of real-time robot-assisted ankle assessment technique [7, 13]. Mechanically, this robot consists of a fixed platform (FP) and a moving platform (MP), of which FP is rigidly connected with the base and the other is moving as a MP for various ankle motions. This robot has an advanced sensing system that includes four single-axis load cells (SLCs) to measure the contraction force of each FFM, three magnetic encoders to track the angular position of each DOF, and a multi-axis load cell (MLC) for measuring ankle torque in a three-dimensional space. Four proportional pressure regulators (PPRs) (FESTO VPPM-6L-L-1-G18-0L6H) are used to control four FFMs. Compared with the most existing platform based ankle robots, the rotational center of this novel prototype coincide with the ankle joint to perform the accurate rehabilitation training. Besides, using four FFMs cannot only provide enough ROM and torque, but also reduce the impedance of the device. Moreover, the real-time ankle assessment unit is composed of SLCs and MLC, which can extract data to assess the performance of patients and realize the advanced control strategies.However, this stage, the MLC is not used in this model based open loop controller.

B. FFM Modeling

FFMs can produce larger force with the same size and contraction length when compared with traditional pneumatic muscle actuators. Thus, FFMs were used as actuators of this AARR in order to increase the torque generation capability. However, accurate modeling of FFMs is critical for control purpose in robotic devices. Sarosi [14] proposed a function approximation for the static force generated by FFM, as shown in equation (1). These parameters were experimentally obtained by using FESTO DMSP-40-300 to drive FESTO DMSP-20-400 respectively for inflation and deflation. It can be seen from equation (1) that the contraction force of FFMs depends on contraction ratio and internal pressure. The specific relation among FFM strain, pressure and the generated force for FESTO DMSP-20-400 is shown in Figure 1, in which the blue line represents inflation and the red line represents deflation.

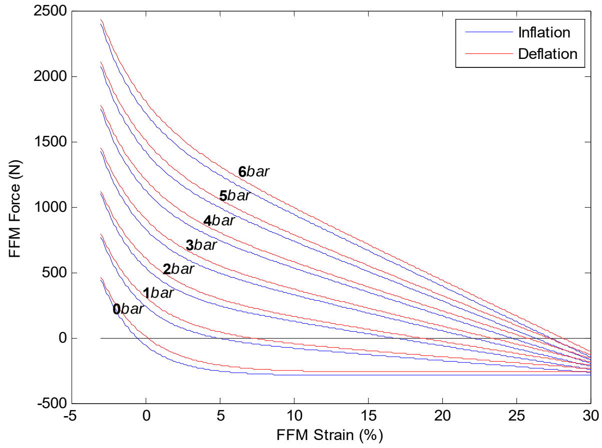

Figure 1. Static model of a FFM (DMSP-20-400N-RM-RM)

$$F(p,k) = (p+a)\cdot e^{b\cdot k} + c\cdot p\cdot k + d\cdot p + e \,. \qquad (1)$$

C. Kinematics

Figure 2 shows the line sketch of an actuator and its position vector on both FP and MP. The lengths of four FFMs are determined by the pose of the MP. Their attachment points on the MP and FP are denoted by ${}^m p_i$ and ${}^f s_i$ respectively. The connection points on the FP are all in the plane $X_f O_f Y_f$. Their position vector ${}^f S_i$ of point ${}^f s_i$ on the FP are defined in equation (2). Similarly, the position vector ${}^m P_i$ of point ${}^m p_i$ on the MP are defined in equation (3). The position vector ${}^f O$ of point O_m on the FP are defined in equation (4).

$${}^f S_i = (x_i^f, y_i^f, 0)^T \,. \qquad (2)$$

$${}^m P_i = (x_i^m, y_i^m, -h)^T \,. \qquad (3)$$

$${}^f O = \overrightarrow{O_f O_m} = (0,0,-H) \,. \qquad (4)$$

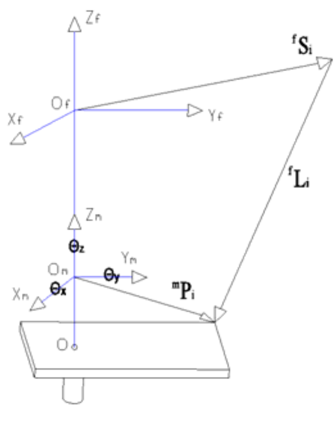

Figure 2. Line sketch of an actuator and its position vector on both platforms

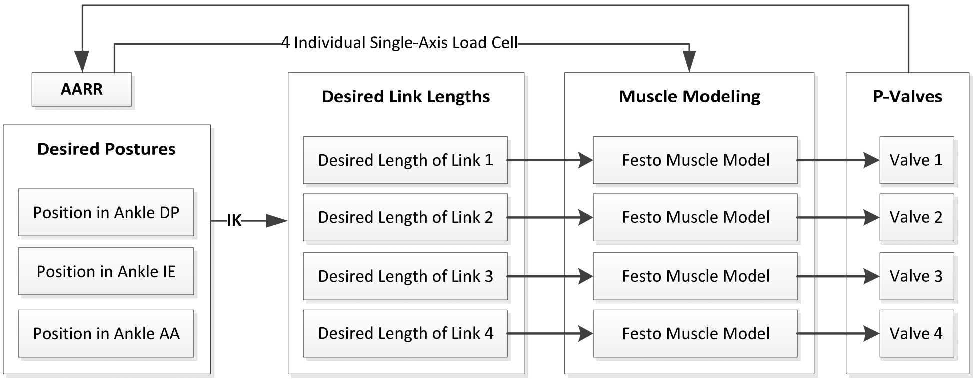

Figure 3. Model based open-loop control of the proposed AARR

${}^{f}R_{m}$ is the rotational transformation matrix of the MP with respect to its initial coordinate system using a fixed axis rotation sequence of $\theta_x,\theta_y,\theta_z$ about X_f,Y_f,Z_f respectively. By this matrix, position vectors on the MP can be described on the FP, see equation (5). This rotation matrix depends on the posture of the MP, as shown in equation (6).

$$ {}^{f}P_i = {}^{f}R_m \cdot {}^{m}P_i \, . \tag{5} $$

$$ \begin{aligned} {}^{f}R_m &= \begin{pmatrix} \cos\theta_z \cos\theta_y & A_{12} & A_{31} \\ \sin\theta_z \cos\theta_y & A_{22} & A_{23} \\ -\sin\theta_y & \cos\theta_y \sin\theta_x & \cos\theta_y \cos\theta_x \end{pmatrix} \\ A_{12} &= -\sin\theta_z \cos\theta_x + \cos\theta_z \sin\theta_y \sin\theta_x \\ A_{22} &= \cos\theta_z \cos\theta_x + \sin\theta_z \sin\theta_y \sin\theta_x \\ A_{31} &= -\cos\theta_z \sin\theta_x + \sin\theta_z \sin\theta_y \cos\theta_x \\ A_{23} &= \sin\theta_z \sin\theta_x + \cos\theta_z \sin\theta_y \cos\theta_x \end{aligned} \quad . \tag{6} $$

$$ {}^{f}L_i = {}^{f}O + {}^{f}R_m \cdot {}^{m}P_i - {}^{f}S_i \, . \tag{7} $$

The position vector ${}^{f}L_i$ of an FFM can be calculated based on equation (7). Further, the magnitude ${}^{f}l_i$ can be obtained for a given set of MP orientations, see equation (8).

$$ {}^{f}l_i = \sqrt{({}^{f}L_i)^T \cdot {}^{f}L_i} \, . \tag{8} $$

D. *Controller Design*

A model based open-loop controller was proposed for this AARR as a preliminary test, see Figure 3. Based on required posture of the MP, desired individual link length could be obtained by inverse kinematics (IK). During the robotic training, real-time contraction force of each FFM could be measured by four SLCs. Based on equation (1), the required pressure for each FFM could be obtained. These values will be respectively delivered to four PPRs to realize the predefined trajectory of the AARR.

III. SIMULATION

Before experiments, MATLAB simulation was conducted to evaluate the feasibility and safety. Figure 4 shows the flow diagram of the model based open-loop controller for this AARR. The predefined robotic motion (a sin wave trajectory with 0.1 Hz frequency, 20° amplitude and zero phase) is only for ankle dorsiflexion and plantarflexion. Ankle dorsiflexion is identified as positive while plantarflexion is negative. By IK, link length required for the individual could be obtained as well as the corresponding muscle strain. Muscle strains are subject to link lengths and robotic configuration. FFM strain is expressed as the ratio of the contraction length to the initial length, as shown in equation (9). Individual pressure value could be further estimated by Sarosi's model [14]. Figures 5, 6 and 7 present the simulation results in terms of individual link length, FFM strain and required pressure. It can be seen that FFN strains are in the normal stroke (no more than 25% contraction). The calculated pressure values are also in the normal range for FFMs and PPRs. Further, there are two models used for the simulation in Figure 7. The legends with subscript H represent the results by FFM model with hysteresis considered (separating inflation and deflation). The others were obtained based on FFM model with only inflation. For late use, inflation and deflation model (IDM) and inflation model (IM) are used to represent these two different models.

$$ FFM\ Strain = (L_{contraction} - L_{initial}) / L_{initial} \, . \tag{9} $$

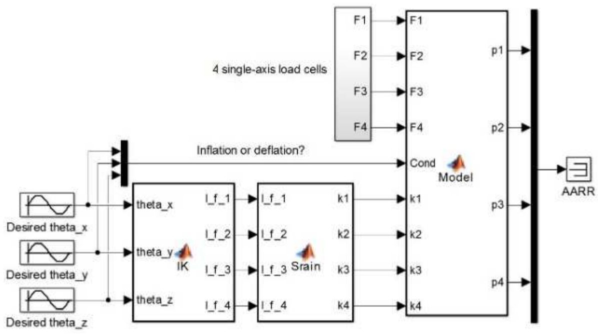

Figure 4. MATLAB simulation block diagram of the model based open-loop controller for AARR

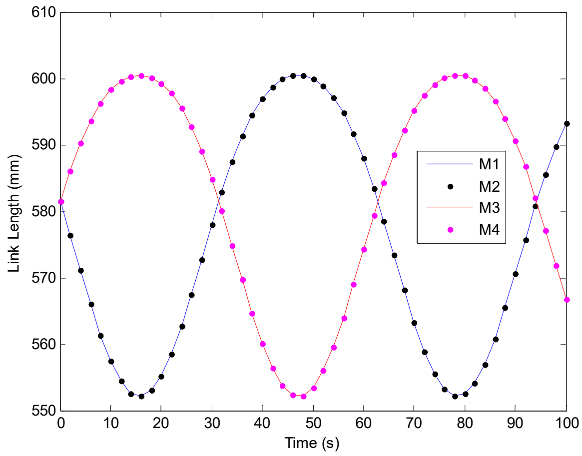

Figure 5. Real-time length of each link in MATLAB simulation

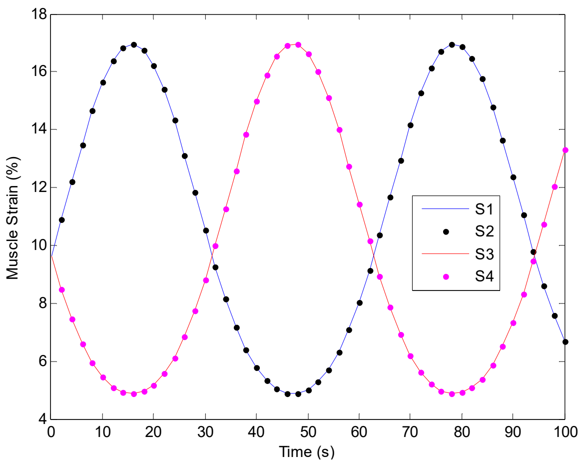

Figure 6. Real-time strain of each FFM in MATLAB simulation

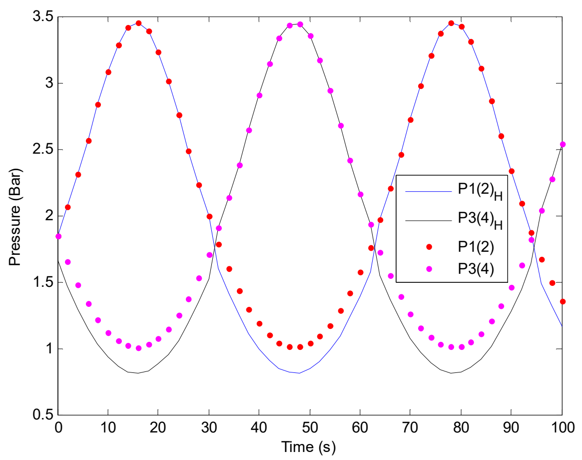

Figure 7. Real-time required pressure of each FFM in MATLAB simulation (H: Hysteresis, equals to IDM)

IV. EXPERIMENTAL RESULTS

A healthy subject (gender: male, age: 29) participated in this study. This study was approved by the University of Auckland, Human Participants Ethics Committee (9348) for experimentation on human subjects, and consent was obtained from this participant. This subject was instructed to sit on a height adjustable chair with one foot strapped on the footplate that is rigidly connected with the MP by the MLC. The shank was strapped on a leg holder but not rigidly to increase comfort. A subjective evaluation on using this AARR was obtained from this participant.

The predefined ankle trajectory in this experiment was the same as that used in MATLAB Simulation. The AARR provided the participant a series of ankle training cycles in dorsiflexion /plantarflexion based on two different models. The trajectory following responses in ankle dorsiflexion /plantarflexion are respectively shown in Figure 8 and 9. Figure 8 shows the tracking performance by IDM while data in Figure 9 were obtained by IM. These two methods behave differently although there is no much difference regarding the achieved training ROM. The graphical results of the robotic training using IM shows that it is more smooth than that using IDM, which is also supported by the subjective feeling of the participant. In Figure 9, there are some sudden changes that are not safe for human users. The reason is obviously shown in Figure 8, in which sudden changes exist in calculating the required pressure when using IDM. Further, it is shown in Figure 8 that the achieved ROM cannot reach as much as predefined ROM, which could be caused by some reasons such as model accuracy and robotic assembly precision. To increase the achieved robotic ROM (actual trajectory 1) in Figure 9, we added a proportional coefficient in calculating required pressure. Accordingly, the achieved ROM (actual trajectory 2) was slightly increased with respect to actual trajectory 1.

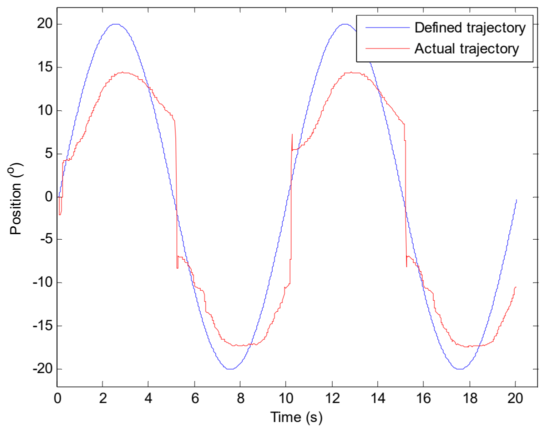

Figure 8. Trajectory following responses by FFM model with hysteresis

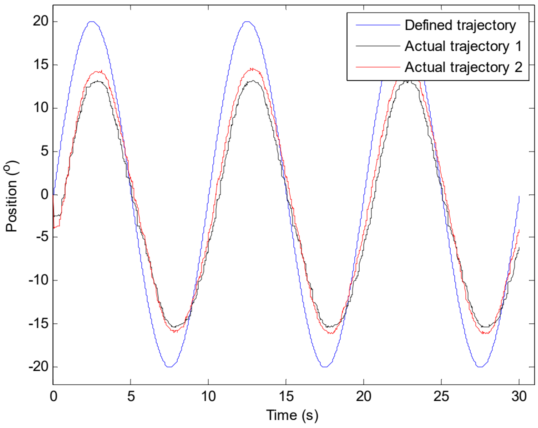

Figure 9. Trajectory following responses by FFM model with only inflation

V. Discussion and Conclusion

This robotic design addressed the aforementioned issues of existing ankle rehabilitation robots. During the robotic training, the participant could keep lower limbs stationary. However, there are two main things to be discussed here. The stroke of FFMs could only contract up to 20%. Long FFMs have to be used to achieve more robotic ROM, which may make the robot too deep when considering the distance between the FP and the MP. The largest torque generation capability and robotic ROM could not be reached simultaneously. Further optimization is needed for a specific application.

To evaluate this robotic design, a model based open-loop control was implemented in this AARR as a preliminary test. The generated robotic training is continuous although it could not track predefined trajectory accurately. As shown in Figure 9, this controller is stable with unknown external disturbance (gravity, friction and patient-robot interaction). However, the controller is suitable for passive ankle training which does not require tracking precision. The control performance is definitely subject to the modeling accuracy of FFMs.

This robotic design has the potential for ankle rehabilitation. The integration of real-time ankle assessment unitallows the realization of advanced control strategies. The proposed open loop controller is stable although the tracking accuracy is not high. Future work will focus on realizing some advanced training modes on this AARR as well as the improvement of trajectory tracking accuracy.

Acknowledgment

This material was based on work supported by the University of Auckland, Faculty of Engineering Research Development Fund -3625057 (Physical Robot-Human Interaction for Performance-Based Progressive Robot-Assisted Therapy) and China Sponsorship Council.

References

[1] S. Siegler, J. Chen, and C. D. Schneck, "The Three-Dimensional Kinematics and Flexibility Characteristics of the Human Ankle and Subtalar Joints—Part I Kinematics1," *Journal of Biomechanical Engineering,* vol. 110, pp. 364-373, 1988.

[2] G. J. Sammarco, *Rehabilitation of the Foot and Ankle*. Missouri, USA: Mosby-Year Book, 1995.

[3] J. Hertel, "Functional Anatomy, Pathomechanics, and Pathophysiology of Lateral Ankle Instability," *Journal of Athletic Training,* vol. 37, pp. 364-375, 2002.

[4] ACC. (2014). *Injury Statistics Tool*. Available: http://www.acc.co.nz/about-acc/statistics/injury-statistics/index.htm#

[5] P. K. Jamwal, "Design Analysis and Control of Wearable Ankle Rehabilitation Robot," Doctor of Philosophy PHD thesis, Mechanical Engineering Department, The University of Auckland, New Zealand, 2011.

[6] H. I. Krebs, J. J. Palazzolo, L. Dipietro, M. Ferraro, J. Krol, K. Rannekleiv, B. T. Volpe, and N. Hogan, "Rehabilitation Robotics: Performance-Based Progressive Robot-Assisted Therapy," *Autonomous Robots,* vol. 15, pp. 7-20, 2003.

[7] M. Zhang, T. C. Davies, and S. Xie, "Effectiveness of robot-assisted therapy on ankle rehabilitation -- a systematic review," *J Neuroeng Rehabil,* vol. 10, p. 30, Mar 21 2013.

[8] M. Girone, G. Burdea, M. Bouzit, V. Popescu, and J. E. Deutsch, "A stewart platform-based system for ankle telerehabilitation," *Autonomous Robots,* vol. 10, pp. 203-212, Mar 2001.

[9] J. Yoon, J. Ryu, and K.-B. Lim, "Reconfigurable ankle rehabilitation robot for various exercises," *Journal of Robotic Systems,* vol. 22(Supplement), pp. 15-33, 2006.

[10] L. Gengqian, G. Jinlian, Y. Hong, Z. Xiaojun, and L. Guangda, "Design and Kinematics Simulation of Parallel Robots for Ankle Rehabilitation," in *Mechatronics and Automation, Proceedings of the 2006 IEEE International Conference on*, 2006, pp. 1109-1113.

[11] C. E. Syrseloudis and I. Z. Emiris, "A parallel robot for ankle rehabilitation-evaluation and its design specifications," in *BioInformatics and BioEngineering, 2008. BIBE 2008. 8th IEEE International Conference on*, 2008, pp. 1-6.

[12] P. K. Jamwal, S. Q. Xie, S. Hussain, and J. G. Parsons, " An Adaptive Wearable Parallel Robot for Ankle Injury Treatments," *IEEE Transactions on Mechatronics,* vol. 19, pp. 64-75, 2014.

[13] M. Zhang, T. C. Davies, Y. Zhang, and S. Xie, "Reviewing effectiveness of ankle assessment techniques for use in robot-assisted therapy," *Journal of Rehabilitation Research & Development,* vol. 51, 2014.

[14] J. Sarosi, "New approximation algorithm for the force of Fluidic Muscles," in *Applied Computational Intelligence and Informatics (SACI), 2012 7th IEEE International Symposium on*, 2012, pp. 229-233.