Soft robot for ankle rehabilitation

1st Dina Al-Shamkhani
Department of Computer Engineering,
University of Basrah
Basrah, Iraq
pgs.dina.ayad@uobasrah.edu.iq

2nd Alaa Al-Ibadi
Department of Computer Engineering
University of Basrah
Basrah, Iraq
alaa.abdulhassan@uobasrah.edu.iq

3rd Maria Elena Giannaccini
Department of Biomedical Engineering
University of Aberdeen, Aberdeen
AB243FX, UK
elena.giannaccini@abdn.ac.uk

***Abstract*— Modern soft robotics integrates pliable materials and advanced control systems to design robots with lifelike flexibility. These adaptable machines excel in navigating intricate surroundings, interacting gently with humans, and tackling tasks requiring dexterity. This paper utilizes a pneumatic muscular actuator (PMA) that leverages pneumatic muscles and advanced technological modalities for the purpose of orchestrating the motion of ankle muscles and joints. This engineered system enables the deliberate extension, contraction, and lateral manipulation of ankle muscles, offering therapeutic assistance to individuals afflicted with conditions such as fractures, muscular atrophy, or requiring rehabilitation. The articulated design yields a soft robot for ankle rehabilitation characterized by its lightweight nature, which provides exercises for the ankle muscles and joints, flexible motion dynamics, robust mechanical integrity, economic viability, and multi-directional mobility attributes.**

Keywords*— *Robotic exoskeletons, Ankle, Pneumatic muscle actuator, soft robot, Rehabilitation

I. INTRODUCTION

Soft robots are often inspired by biological systems which consist of soft materials. There are several advantages of soft robots compared to conventional robots; safe human-machine interaction, adaptability to wearable devices, simple gripping system, and so on [1], [2]Soft robotics technologies are paving the way toward robotic abilities which are vital for a wide range of applications, including manufacturing, manipulation, gripping, human–machine interaction, locomotion, and more[3]–[5],[6][7][8][9].

Soft robotic concepts for lightweight, affordable assistive devices with flexible materials and forgiving interactions between the robot and the complex human ankle joint have been shown to be successful. Soft robotics' compliant materials reduce the amount of computation required to align joints, prevent the placement of bulky components on the foot, and provide pleasant actuation techniques for ankle rehabilitation [10].

The past decade has focused on the significance of designing exoskeleton robots capable of producing forces at the level of the lower limbs or other wearer body parts. As a result, an expanded definition of the robotic community has been registered to include exoskeleton robots. The majority of recent research on wearable robotics derives from their application in neuro-rehabilitation, where the exoskeleton system is used to dynamically assist the patient's appendage in performing specific activities.

This paper depicts the development of novel contraction pneumatic soft actuators for utilization in a power augmentation soft robot to be used in the physiotherapy of human ankle joint injuries, such as those of athletes, recovery after stroke, and aiding in walking normally for those with muscular dystrophy, chronic ankle instability (CAI) is a long-term impairment that is often brought on by repeated ankle sprains, in which the tendons that surround the joint are stretched above their normal length and permanently distort when an unexpected occurrence of inversion or eversion results from lateral ankle buckling, which places an excessive amount of strain on the tendon, an ankle sprain may happen [11]–[16]. Therefore, this soft robot is designed for ankle rehabilitation, the robot adopts six pneumatic muscles inside, which are environmentally and human-friendly, safe, and without any electric motors.

The rest of this paper will be structured as follows. Firstly, Related work is dealt with in Section 2. In Section 3, The anatomy of the muscles and bones of the ankle joint is illustrated. In Section 4, the proposed robot The muscles, their construction, and the materials used to construct the robot's aerobic muscles and to construct the fully flexible robot and its operation are described in detail. Finally, in Section 5, the conclusion is drawn.

II. RELATED WORK

Researchers have developed a strong reputation for soft actuators, especially in recent years. Soft robotics has therefore seen significant usage in a variety of fields. Such robots are of interest to researchers in a variety of disciplines, including material science, physics, biology, computer science, and control engineering.

A possible alternative has evolved in the form of soft robotic exosuits constructed of functional fabrics that resemble clothing[17]– [20] exosuits use several strategies to provide help when walking.

Yupeng Ren and others [21] have suggested a robotic wearable ankle gadget. Patients are guided through the motor relearning process using an isometric torque-generating mode with real-time feedback. In the passive stretching mode, the wearable robotic device securely and aggressively extends the ankle to the extreme dorsiflexion throughout its range of motion. Meanwhile, other researchers [22]soft robotic socks that can compliantly actuate the ankle joint during the initial stages of stroke recovery has been designed. The device is equipped with soft extension actuators, which, when inflated, guide the foot into plantarflexion and extend when deflated, returning to their initial conformations, also Carly M. Thalman et al.[23] proposed a wearable soft robot designed for ankle assistance, and a pilot human study of its use. Using two novel pneumatically powered soft actuators, the SR-AFO is designed to assist the ankle in multiple degrees of freedom during standing and walking tasks. The flat fabric pneumatic artificial muscle (ff-PAM) contracts upon pressurization and assists ankle plantarflexion in the sagittal plane. The multi-material actuator for variable stiffness (MAVS) aids in supporting ankle inversion/eversion in the frontal plane, the authors in[24], [25] Soft robotic ankle-foot orthosis (SR-AFO) with two ff-PAMs, which are pneumatic artificial muscles made of flat fabric. The entrainment capabilities of a lighter, soft robotic orthosis were compared to those of its heavier, rigid robotic competitors. Periodic pneumatic plantarflexion perturbations equal to the increase derived from the subject's preferred gait frequency were administered to the ankle to test the SR-AFO's ability to manifest gait entrainment. In contrast to previous work, this research employs a soft robot with lightweight tube muscles. These muscles contract by pumping air, allowing flexible movement in various ankle joint directions.

III. ANATOMY OF THE FOOT AND ANKLE

The joint capsule, ligamentous support, and bony congruence all contribute to the ankle joint's stability. Three primary supporting ligaments make up the syndesmosis that forms the inferior tibiofibular joint. First, there is the AITFL or anterior inferior tibiofibular ligament. This flat, powerful ligament connects the lateral malleolus' anterior edge to the tibia's anterolateral tubercle. Both superficial and deep sections make up the posterior inferior tibiofibular ligament (PITFL). The superficial part works with the AITFL to keep the fibula firmly inside the incisura of the tibia. The deep part goes from the posterior edge of the tibia to the osteochondral junction on the posteromedial side of the distal fibula [26].

Figure 1a shows functional motor neuron circuits and the muscles that are engaged to carry out the intended body motion. The primary motor cortex on one side of the brain is damaged by a stroke, and the brain lesions result in impaired movement on the opposite side of the body. Brain reorganization, or the brain's capacity for change through time, is known as neuroplasticity, and effective recuperation makes it possible for exercise therapy in stroke rehabilitation to reduce muscle atrophy and encourage nerve healing [27].

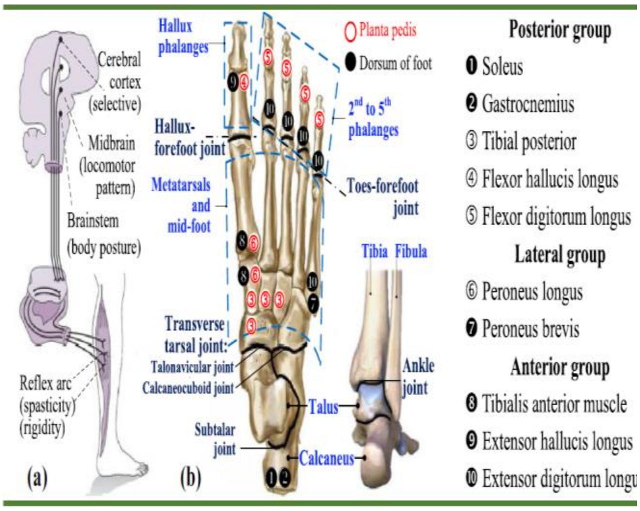

Fig. 1. Schematics illustrating M3R for post-stroke. a Motor neuron pathway. b Five-segment model and muscle attachments [27]

IV. CONTRACTION PNEUMATIC MUSCLE ACTUATOR AND THE ROBOT DESIGN

This section explains how to build the pneumatic muscles, their sizes, the materials used in the construction of pneumatic muscles, and how to connect the materials to build the entire muscle. It also mentions how to build a flexible robot, operate it manually, and its movements and muscles

A. *Contraction pneumatic muscle structure*

The contraction muscle is made up of an inner tube and a braided sleeve of the same length and diameter. Also, there are two aluminum caps, one has a port for air to enter the muscle, and the other is close. The braided sleeve's length was anticipated to match the inner rubber tube's length in order to guarantee that the braided angle was less than 54.7°. If pressure is applied, it causes an expansion in a radial direction on the muscle, increasing the angle between the threads, which leads to an increase in diameter and a shortening of the length of the muscle. In Figure 2, the structure of the contraction pneumatic muscle,

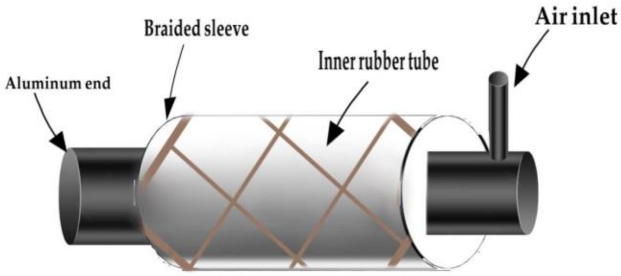

Fig. 2. The structure contraction pneumatic muscle.

B. *Materials and Mehtodes*

A variety of materials, including rubber inner tubes, are used to construct the pneumatic muscles of this robot, which depend on internal air pressure. It is a 1.6 cm diameter tube that is used by bicycles. It has a stretchable, shrinkable material construction and is simple to use. The single tube used for the front muscle was 40 cm long, the other lateral tubes were 26 cm long, and the posterior tubes were 26 cm long. Six pneumatic muscles are used in this particular robot's ankle region.

In order to shield the tube from outside effects and to assist in determining the orientations of the muscles, a braided sleeve with a diameter of 1.6 cm and lengths of 40 cm for the anterior muscle, 26 cm for the lateral muscles, and 26 cm for the posterior muscle was also utilized.

On both ends of the muscles, two-cylinder aluminium caps were used. The length of the first is 4 cm and the diameter is 2.2 cm, which contains a hole inside it to pass air, and the length of the second is 3 cm at a similar diameter.

One of the aluminium covers contains an opening to help pump air through it to the muscle. In this robot, aluminium caps were placed on the inside of the end of the tube at both ends after constructing the pneumatic muscles using the previously discussed components and a rubber tube.

The rubber tube was completely covered in the braided sleeve, and the covers were attached to the tube using a water cap and tape so that they would not move out of place when air was pumped into the tube, as shown in Figure 3.

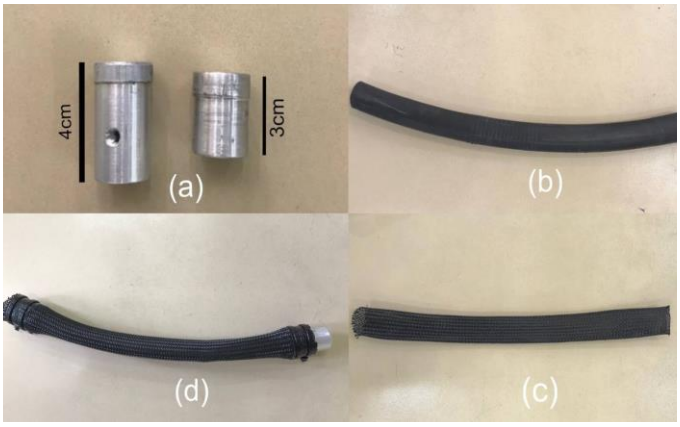

Fig.3. The materials used in building the pneumatic muscle and the shape of the muscle. (a) The Aluminum caps (b) The rubber tube (c) The braided sleeve (d) The fill shape of the contraction muscle covered with a braided sleeve.

After the muscles were completed and worked, they were tested and the rate of contraction that occurred in each muscle was measured. The air was pumped into each muscle with a pressure of 3 bar, and the contraction rate for the front muscle became 8 cm from its original length. The back muscle has a contraction rate of 5 cm, and the side muscles have an amount of contraction is 5 cm, and the percentage of contraction was appropriate because it gives an appropriate movement to the foot when lifting it and doing the exercises. This design is used for a robot that specializes in its work to do physiotherapy for the ankle area and the ankle joint, where a medical shoe was used that had belts to tie it to the foot and this shoe was placed on a base made of rubber Teflon material. This base was perforated with 6 holes, a front hole in front of the foot near the toes in the middle, a hole behind the ankle in the middle, two holes on the left side of the foot, and two holes on the right side of the foot in order to fix the muscles on it. Rubber Teflon material was used because it bears a heavy weight and is suitable and light in weight. The muscles were connected to the thigh area using a fibrous thread and tied around the thigh through the use of The rubber Teflon material is also designed from this material, pieces are placed around the leg and contain a hole from the side to be worn easily, as this side hole contains a side belt to tie it around the leg and a belt was placed with these pieces extending from the thigh area to the waist of the human body that connects with the waist With a belt to fix the pieces and prevent them from moving from their place when the robot is running, as shown in Figure 4.

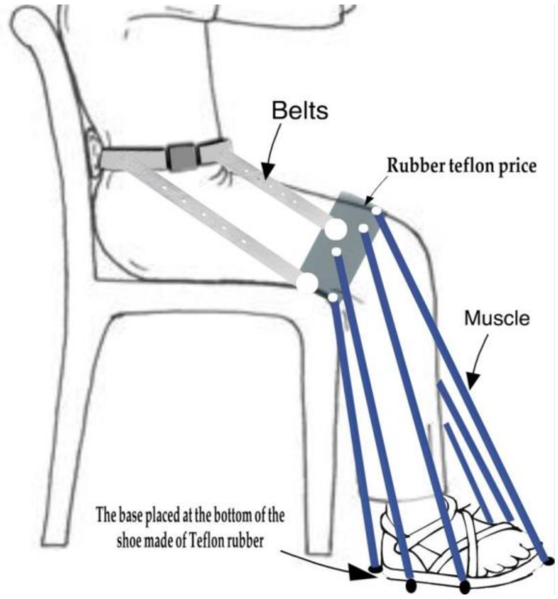

Fig.4. Illustration of designing muscles, pieces, and belts.

C. *Fabrication*

The contracting muscles approved for their work in the air were used for this robot, where the number used is 6 muscles, and this number was used because it gave an appropriate movement when trying it, as these muscles consist of a tube measuring 17 in diameter, and a sleeve with a diameter of 17 cm was used, as the first one was placed forward from the foot and its length was the muscle is 40 cm without ends. Two muscles were placed on the right side of the foot, their length was 26 cm. Two muscles of 26 cm were also placed on the left side, and one was placed from the back of the foot near the ankle. Its length was 26 cm. The reason for the length of the front muscle is 40 because the distance of the leg is long from the bottom of the knee to the foot needs a proportion of movement that raises the foot appropriately, so a length of 40 cm was made. After completing the six muscles, the rubber Teflon material was used, from which a base was made to be placed under the medical shoe that the patient wears, and the benefit of it in order to fix the shoe on it and fix the six muscles on it, where its measurements were taken and it was cut using a computer numerically controller machine cutter (CNC) used to cut some solid and rubber materials the length of the base is 35 cm The width of the piece from the middle is 10 cm and with the side holes the width is 16 cm and its height is 1cm. Figure 5 shows the base made of Teflon rubber that is placed under the base of the shoe.

Fig.5. The Teflon rubber piece that is placed under the base of the shoe.

This piece, which was placed as a base under the shoe, contains 6 holes on the sides, front and back, which are used to fix the six muscles on it, while it contains 3 holes in the middle to fix the shoe on it using iron screws, which were used to fix the muscles and the shoe on the base made of rubber Teflon, Figure 6 demonstrates the fixation of the muscles and the shoe on the base made of Teflon

Fig.6. The shoe and the muscles are attached to the base of Teflon rubber.

Two pieces made of rubber Teflon were also used to be placed around the thigh directly above the knee length is 21cm, its width is 8 cm, and its height is 1cm. The benefit of these pieces is to fix the six muscles from the top of the leg and thigh, where holes were placed in these pieces and screws were placed in them in order to fix the muscles in them containing these pieces Placed around the thigh on one side hole in which a belt is attached to fix it on the thigh and tie it. Figure 7 shows the pieces that are placed around the thigh made of rubber Teflon.

Fig.7. The piece that is placed around the thigh to fix the muscles in it from the top.

A piece of light and soft sponge was placed on the inside of the cut around the thigh to reduce pain when tightly wrapped around the thigh. The cut does not cause harm to the patient's thigh when wearing the robot. Figure 8 shows the spongy piece placed on the inside of the cut around the thigh

Fig.8. A piece of light and soft sponge is placed inside the piece around the thigh.

The muscles were fixed on the pieces placed around the thigh from the top using six fibrous thread that is resistant to pulling and strong and does not break easily. The reason for using the threads is because they are light in weight and give flexible and smooth movement to the robot. The length of the thread for the front muscle is 22 cm and the length for the back muscle is 16 cm. The length of the threads for the lateral muscles from the left side and the right side is 28 cm, where each muscle was wrapped from on the pieces and installed on the pieces placed around the thigh of iron as shown in Figure 9

Fig.9. The six muscles are attached to the threads from the top with pieces of Teflon around the thigh from the top.

After completing the connection of the muscles to the base from the bottom and from the pieces placed around the thigh and connecting the threads to the muscles and pieces of rubber Teflon placed around the thigh, three belts were used the length of the belts extending from the top of the thigh to the waist is 72 cm, and the width is 4 cm. The second belt extending from the back of the leg to the waist is 84 cm, and the width is 4 cm. It extends to the belt placed around the waist, and the third belt was installed from the back from the pieces placed around the thigh and extends to the belt placed around the waist. The benefit of these belts is to install the robot well and appropriately. When it is running, the pieces do not move and slide down when turned on to remain fixed in their place and do not withdraw or move from their place Figure 10 shows the belts placed around the waist and the pieces around the thigh from the front and back the belts are of the two-sided type placed around the pieces, while the belt placed around the waist is a resistant fibrous belt.

Fig.10. The belts are placed around the pieces and the belts are placed around the waist.

After completing the connection of all muscles and belts, fixing the muscles to the thigh and the base of the shoe, and tying the belts and fixing them with the waist belt, the robot was completed and worn, and an integrated robot was obtained, as shown in Figure 11.

Fig.11. The integrated shape of the robot. (a)The shape of the robot and the frontal muscle. (b) The shape of the robot from the side and the lateral muscles. (c) The shape of the robot and the back muscle

D. Manual Operation

The robot operated manually after all its parts were fully connected, and its six muscles were examined and tested. The air hose was placed in the six muscles through the holes at the end of each muscle and secured. Air was started to be pumped through the compressor in the laboratory gradually to the pneumatic muscles, and a flexible and smooth movement was obtained for each direction of the ankle joint. When air was pumped to the anterior muscle, an upward movement of 8 cm was obtained because the muscle shrinks when air is pumped into it by 8 cm, and when the air is emptied, it returns to its normal position. The posterior muscle pulled the ankle joint back by 5 cm, and also for the muscles on the right and left sides, we got a movement of pulling the ankle joint to the left by 5 cm. See Figure 12, which shows robot movements of the ankle joint for each side of the ankle joint. Component.

Table 1 below shows the results we obtained for the length difference of the pneumatic muscles and the contraction rate of each muscle, where the pressure is equal for each muscle and its value is 3 bar.

These movements are flexible, smooth and comfortable for the ankle joint and its muscles, and the proportion of movement of the ankle joint for each side and each direction is appropriate.

Fig.12. The robotic movements of the ankle joint (a) Forward motion of the ankle. (b) Posterior movement of the ankle. (c) Movement towards the right of the ankle. (d) Movement towards the left of the ankle joint

Table [1]

Shows the percentage change in the length of the pneumatic muscles after pumping air into them at a pressure of 3 bar

The PMA	The normal length of the PMA	The length of PMA at pressure 3bar
Front muscle	40 cm	32 cm
Back muscle	26 cm	21 cm
Left muscles	26 cm	21 cm
Right muscles	26 cm	21 cm

The movement on the right side of the ankle joint was a little high because this joint is limited in the movement of its height and a little. These movements are comfortable for the ankle joint, flexible in all directions, and all air muscles have the same pressure and equal amount pumped, and the highest pressure used is 3 bar.

V. CONCLUSION

This article presents the design of a robot with pneumatic muscles used in physiotherapy for the joint, ankle, and leg muscles, as it consists of six pneumatic muscles that rely on pumping air into them. This robot is installed on the thigh area from above, and a flexible shoe is worn on the foot and wrapped around the ankle area using belts attached to the shoe. It gives an upward movement and pulls the ankle joint up when the air is pumped into the anterior air muscle, and when the air is emptied, the ankle returns to its normal position, as well as movements towards the back and sides concerning the rest of the muscles on the right, left, and behind. This robot is worn by a person while he is sitting in a specific place, and his feet are free to move. The air was pumped and controlled manually, and we obtained movements in different directions that were flexible and suitable for the ankle joint.

VI. ACKNOWLEDGEMENT

I would like to express my deepest and sincerest thanks and appreciation to the Department of Computer Engineering at the University of Basrah, which provided a good laboratory, a suitable environment, and materials to work in for my research experiments.

REFERENCES

[1] C. Lee *et al.*, “Soft robot review,” *International Journal of Control, Automation and Systems*, vol. 15, no. 1. Institute of Control, Robotics and Systems, pp. 3–15, Feb. 01, 2017. doi: 10.1007/s12555-016-0462-3.

[2] A. Esquenazi, M. Talaty, and A. Jayaraman, “Powered Exoskeletons for Walking Assistance in Persons with Central Nervous System Injuries: A Narrative Review,” *PM and R*, vol. 9, no. 1. Elsevier Inc., pp. 46–62, Jan. 01, 2017. doi: 10.1016/j.pmrj.2016.07.534.

[3] N. El-Atab *et al.*, “Soft Actuators for Soft Robotic Applications: A Review,” *Advanced Intelligent Systems*, vol. 2, no. 10, p. 2000128, Oct. 2020, doi: 10.1002/aisy.202000128.

[4] H. T. Hendricks, J. Van Limbeek, A. C. Geurts, and M. J. Zwarts, “Motor recovery after stroke: A systematic review of the literature,” *Arch Phys Med Rehabil*, vol. 83, no. 11, pp. 1629–1637, Nov. 2002, doi: 10.1053/apmr.2002.35473.

[5] H. Al-Fahaam, S. Davis, and S. Nefti-Meziani, “Wrist Rehabilitation Exoskeleton Robot based on Pneumatic Soft Actuators.”

[6] D. Al-Shamkhani, F. Al-Farhan, and A. Al-Ibadi, “The Wearable Foot Rehabilitation Soft Robot,” in *2021 International Conference on Communication & Information Technology (ICICT)*, IEEE, Jun. 2021, pp. 197–201. doi: 10.1109/ICICT52195.2021.9568432.

[7] Gazi Üniversitesi, Marmara Üniversitesi, and Institute of Electrical and Electronics Engineers, *2022 9th International Conference on Electrical and Electronics Engineering (ICEEE 2022) : Alanya, Turkey, March 29-31, 2022*.

[8] H. Al-Mosawi, A. Al-Ibadi, and T. Abdalla, “A Comprehensive Comparison of Different Control Strategies to Adjust the Length of the Soft Contractor Pneumatic Muscle Actuator,” *Iraqi Journal for Electrical and Electronic Engineering*, vol. 18, no. 2, pp. 101–109, Dec. 2022, doi: 10.37917/ijeee.18.2.13.

[9] H. A. Mohsen, A. Al-Ibadi, and T. Y. Abdalla, “Different Types of Control Systems for the Contraction Pneumatic Muscle Actuator,” in *2022 8th International Conference on Control, Decision and Information Technologies (CoDIT)*, IEEE, May 2022, pp. 956–961. doi: 10.1109/CoDIT55151.2022.9804047.

[10] Paris, Aleix, Brett T. Lopez, and Jonathan P. How. "Dynamic landing of an autonomous quadrotor on a moving platform in turbulent wind conditions." *2020 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2020.

[11] J. G. Garrick, “The frequency of injury, mechanism of injury, and epidemiology of ankle sprains*.”

[12] H. Yan and C. Yang, “Design and validation of a lower limb exoskeleton employing the recumbent cycling modality for post-stroke rehabilitation,” *Proc Inst Mech Eng C J Mech Eng Sci*, vol. 228, no. 18, pp. 3517–3525, Dec. 2014, doi: 10.1177/0954406214527578.

[13] L. N. Awad *et al.*, “Reducing Circumduction and Hip Hiking During Hemiparetic Walking Through Targeted Assistance of the Paretic Limb Using a Soft Robotic Exosuit,” *Am J Phys Med Rehabil*, vol. 96, no. 10, pp. S157–S164, Oct. 2017, doi: 10.1097/PHM.0000000000000800.

[14] G. D. Fulk, C. Reynolds, S. Mondal, and J. E. Deutsch, “Predicting home and community walking activity in people with stroke,” *Arch Phys Med Rehabil*, vol. 91, no. 10, pp. 1582–1586, 2010, doi: 10.1016/j.apmr.2010.07.005.

[15] J. Wissel, L. D. Schelosky, J. Scott, W. Christe, J. H. Faiss, and J. Mueller, “Early development of spasticity following stroke: A prospective, observational trial,” *J Neurol*, vol. 257, no. 7, pp. 1067–1072, Jul. 2010, doi: 10.1007/s00415-010-5463-1.

[16] V. Ticllacuri, G. J. Lino, A. B. Diaz, and J. Cornejo, “Design of Wearable Soft Robotic System for Muscle Stimulation Applied in Lower Limbs during Lunar Colonization,” in *Proceedings of the 2020 IEEE 27th International Conference on Electronics, Electrical Engineering and Computing, INTERCON 2020*, Institute of Electrical and Electronics Engineers Inc., Sep. 2020. doi: 10.1109/INTERCON50315.2020.9220206.

[17] J. Bae *et al.*, “Biomechanical mechanisms underlying exosuit-induced improvements in walking economy after stroke,” *Journal of Experimental Biology*, vol. 221, no. 5, Mar. 2018, doi: 10.1242/jeb.168815.

[18] L. N. Awad *et al.*, “A soft robotic exosuit improves walking in patients after stroke,” 2017. [Online]. Available: http://stm.sciencemag.org/

[19] K. Schmidt *et al.*, “The myosuit: Bi-articular anti-gravity exosuit that reduces hip extensor activity in sitting transfers,” *Front Neurorobot*, vol. 11, no. OCT, Oct. 2017, doi: 10.3389/fnbot.2017.00057.

[20] S. Sridar, Z. Qiao, N. Muthukrishnan, W. Zhang, and P. Polygerinos, “A soft-inflatable exosuit for knee rehabilitation: Assisting swing phase during walking,” *Frontiers Robotics AI*, vol. 5, no. MAY, 2018, doi: 10.3389/frobt.2018.00044.

[21] Y. Ren, Y. N. Wu, C. Y. Yang, T. Xu, R. L. Harvey, and L. Q. Zhang, “Developing a Wearable Ankle Rehabilitation Robotic Device for in-Bed Acute Stroke Rehabilitation,” *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 25, no. 6, pp. 589–596, Jun. 2017, doi: 10.1109/TNSRE.2016.2584003.

[22] F. Z. Low, J. H. Lim, and C. H. Yeow, “Design, characterisation and evaluation of a soft robotic sock device on healthy subjects for assisted ankle rehabilitation,” *J Med Eng Technol*, vol. 42, no. 1, pp. 26–34, Jan. 2018, doi: 10.1080/03091902.2017.1411985.

[23] C. M. Thalman, T. Hertzell, M. Debeurre, and H. Lee, “Multi-degrees-of-freedom soft robotic ankle-foot orthosis for gait assistance and variable ankle support,” *Wearable Technologies*, vol. 3, Aug. 2022, doi: 10.1017/wtc.2022.14.

[24] C. Thalman, M. P. Debeurre, and H. Lee, “Entrainment during Human Locomotion Using a Soft Wearable Ankle Robot,” *IEEE Robot Autom Lett*, vol. 6, no. 3, pp. 4265–4272, Jul. 2021, doi: 10.1109/LRA.2021.3066961.

[25] C. M. Thalman, T. Hertzell, and H. Lee, *Toward A Soft Robotic Ankle-Foot Orthosis (SR-AFO) Exosuit for Human Locomotion: Preliminary Results in Late Stance Plantarflexion Assistance*. 2020. doi: 10.0/Linux-x86_64.

[26] E. J. C. Dawe and J. Davis, “(vi) Anatomy and biomechanics of the foot and ankle,” *Orthop Trauma*, vol. 25, no. 4, pp. 279–286, Aug. 2011, doi: 10.1016/j.mporth.2011.02.004.

[27] J. Jiang, K. M. Lee, and J. Ji, “Review of anatomy-based ankle–foot robotics for mind, motor and motion recovery following stroke: design considerations and needs,” *Int J Intell Robot Appl*, vol. 2, no. 3, pp. 267–282, Sep. 2018, doi: 10.1007/s41315-018-0065-7.