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Biomechanical Integration of an Active Prosthetic Ankle for Motorcycle Riding in Lower Limb Amputees

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Abstract* - There are over one million lower limb amputees in India alone. Due to societal stigmas, many individuals are unable to work or live independently, as they rely on insufficient prosthetic limbs that require much more effort to move and result in abnormal gait patterns. The high-performing prosthetic feet available for several thousand rupees in India are distinct from the low-cost, non-functional prosthetic legs mentioned above. Our mission addresses this discrepancy by developing an active ankle movement lower limb prosthetic leg, specifically designed for bike riding. Typically, riders apply forces between 100 and 200 Newtons (N) to the brake pedals and between 5 and 10 N to the gear shifters. This project utilizes a servo motor to control ankle movement, a microcontroller to process information, and EMG sensors to detect muscle movements. By replicating the rider's ankle action, this system significantly improves control and safety without occupying additional space. In addition to enhancing ankle mobility, the technology provides users with real-time feedback through vibrations, offering a more accurate and quicker response in sync with the body's movements while riding. Furthermore, the bike's space-saving design and user-friendly operation are enabled by a remote-control system installed on the bike handle. This allows users to move with greater ease, independence, and the ability to engage in activities such as riding a motorcycle and living actively among others. Ultimately, it improves their quality of life and promotes a sense of social belonging.
Keywords: **Prosthetic Leg, Servo Motor, Remote-Control, Real-Time Feedback, Independence**

I. INTRODUCTION

Lower limb amputees face significant challenges in modern society, and this issue remains prevalent, particularly in countries like India, where the number of amputees exceeds one million and continues to increase by around 23,500 per year. These individuals encounter a harsh reality, both due to societal stigma and the lack of access to proper prosthetics. The wide gap between expensive, high-quality prosthetic feet and cheaper, inferior options exacerbates their difficulties. A major concern in this situation is that prosthetic technology has yet to innovate adequately to meet the specific needs of lower limb amputees. Traditional prosthetic options are not only inadequate, falling far short of what athletes and active individuals require, but they are also uncomfortable and costly, leaving a significant gap for transformational treatments.

In this context, the development of a lower limb prosthetic leg with active ankle mobility offers a ray of hope. This innovation could be a game-changer for lower limb amputees, providing an enhanced sense of mobility, independence, and social integration through a unique design tailored specifically for motorcycling. The rich and diverse literature on lower limb prosthetics is an excellent resource for discovering many novel ideas and insights that could address the complex problems faced by amputees.

An example of this can be seen in the work of Amiot *et al.,* who were the first to develop a single degree-of-freedom, passive hydraulically actuated prosthetic ankle for walking and running over level and uneven terrain [2]. This new design, with hydraulic circuitry combined with weight activation, has already demonstrated adaptation to slopes during prototype testing and significantly more energy storage than a typical prosthesis. This highlights the pressing demand for innovative solutions within prosthetics [3].

When introduced as a robotic knee/ankle prosthesis platform in 2018, the Open-source Leg (OSL) was recommended as a solution for the development of technology and accessibility due to its scalability. In this framework, Alleva *et al.,* presented a new design for a powered ankle-foot prosthetic (PAPP) that aims to reproduce both the wide range of motion and push-off power generation in normal gait, as described by Geyer *et al.,* [1]. Despite a few restrictions on using specific components, this creative design has the potential to optimize ankle angle range and push-off force through iterative optimization based on meticulous kinematic-dynamic modeling.

Baker discusses the biomechanical aspects of a prototype ankle joint aimed at improving post-stroke walking. This study is the first to demonstrate increases in stance phase duration and ankle angular range of motion based on a novel design tested on an individual with post-stroke hemiparesis as well as on healthy controls, marking an important step towards successful rehabilitation in stroke patients [4]. Brockett and Chapman highlight the complexity of ligament function and the surgical implications for mobility in their comprehensive insights into ankle biomechanics, which are fundamental for guiding surgical decision-making with respect to optimal functional outcomes [5].

Despite today's standardization concerns, EMG-driven control of lower limb prostheses holds great potential. Through extensive analysis, researchers show how various neuro-controller types could be incorporated, enabling controlled spatio-temporal patterns and improving the quality of life for amputees [6]. Additionally, Crenna *et al.,* emphasize practicality and simplicity in the functional design of an intelligent transtibial prosthesis, which is designed to mimic healthy foot range-of-motion using locally available materials [7].

A comprehensive discussion of the delicate balance required for foot stability and ambulation is provided by Dawe & Davis, which is important for achieving optimal surgical and postoperative functional outcomes [8]. In their modeling study and feasible implementation, they performed a systematic literature analysis to summarize finite element models of the lower limb when simulating various activities. This analysis incorporates both biomechanical behaviors related to soft tissue internal mechanics and the ways in which residual limbs and prostheses are mechanically joined [9].

To address the immediate need for prosthetic solutions that are both available and affordable, research has been conducted on low-cost materials with the potential to improve comfort and mechanical properties in prosthetic sockets [10]. A comprehensive review has been presented on the causes of amputation, prosthetic development, designs, and controls, with an emphasis on psychosocial effects. Patent design trends have also been covered in this article, providing insights that will aid progress in the burgeoning field of prosthetic technology by encouraging innovation and knowledge sharing [11].

Tucker *et al.,* have developed control algorithms that emphasize intelligent interfaces for natural connections between the user's sensory-motor system and wearable robotic systems [13]. This article is further studied by Canino and Fite to examine haptic feedback in amputation rehabilitation, demonstrating its utility in EMG activities [14]. Tkach *et al.,* focus on technological advancements that allow the myoelectrically controlled powered prosthesis to be remotely sensed, thus improving the precision of ankle movement [15]. Dimitrov *et al.,* introduced a two-degree-of-freedom (DoF) control interface for below-knee amputees [16].

Grimmer & Seyfarth analyzed the complexity involved in human gait and suggested specific areas of potential research, marking a departure from unpowered prosthetic systems [17]. Grimmer *et al.,* also considered series elastic actuators (SEA) in monoarticular hip joints during propulsion [18]. Actis *et al.,* have studied trunk kinematics and adaptive muscle-reflex controllers [19, 20], respectively, implicating consequences on the functioning and adaptability of prosthesis usage. Wang et al. aimed to increase gait stability and symmetry by integrating steady rhythmic sensory feedback into an ankle robot [21].

In Figure 1, Song *et al.,* study the link between muscle strain and motor control after amputation. They specifically state that resting any individual group of agonist-antagonist muscles will interfere with natural motor control [22].

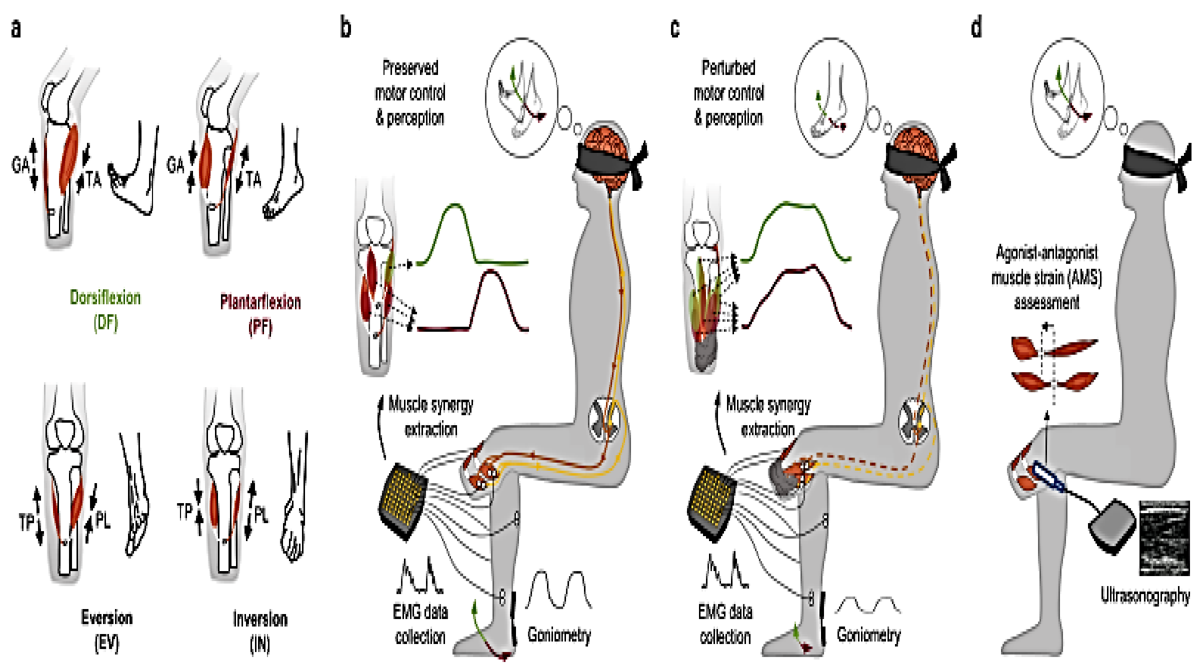

Fig. 1 Use of EMG sensor for mimicking ankle movement in amputee [22]

II. ACTIVE PROSTHETIC ANKLE DESIGN

The different views of the active prosthetic ankle assembly are as follows.

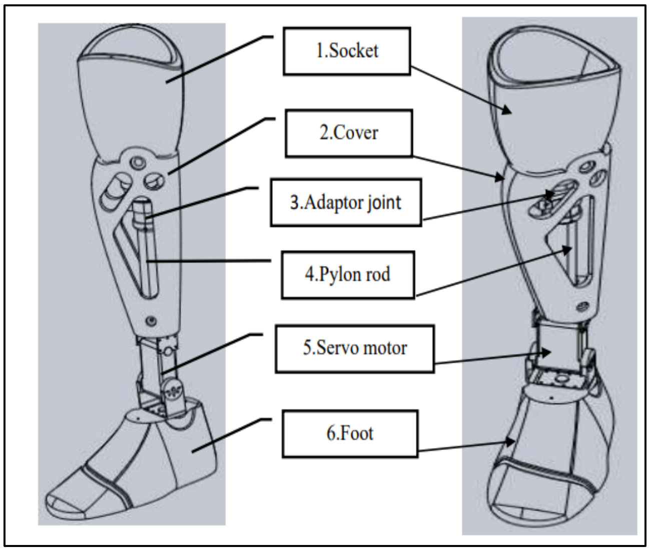

Fig. 2 Assembly of active prosthetic ankle

In Fig. 2, the three-dimensional active prosthetic ankle assembly viewed from side and front view is shown, respectively. The prosthetic ankle assembly are divided into: Active Prosthetic Ankle Assembly, then Socket with Pylon Rod using adaptors on the top side of pylon tube, and bottom side of pylon tube assembled with Servo Motor. This all assembly is inside a 3D printed cover made with PLA material.

Components Active prosthetic leg consists of the following.

1. Socket (The Attachment of the Prosthesis to a Residual Limb): Custom made according to the requirement and position of amputation (dome is different as per where leg is being cut).

2. Cover (Also Covering the Foot Part): A protection shell that covers its inner components as well, within this component will be placed all electronics such Nano Arduino, EMG sensor and any other needed to perform global functionalities. Besides, it has the battery life display and is available for disassembly to ease maintenance.

3. Adaptor Joint: It is used to link pylon tube and socket, acting as an intermediary component of the socket. This will allow us to fix the entire assembly of active prosthetic ankle into socket and can also change its orientation according to requirement as every person have different style of walking. Standard adaptors are selected.

4. Pylon Tube (Located Just Under the Adapter Joint, it Adds Rigidity and Connects Back to Lower Limb Elements of Prosthesis): It makes load carrying of amputee easier. Its height is varied as per the height of amputee and material is changed as per weight of amputee. In this project aluminium alloy is used.

5. Servo Motor: This high-strength motor enables accurate ankle flexion based on input from a microprocessor listening to EMG sensor or remote. This model allows an amputee to step-on-shift and brake during biking force. Servo motor with 150 kg/cm2 torque at 10 V is used.

6. Foot: Located below the servo motor, this part emulates a real foot to stabilize and assist during motorcycle rides. Its foot rest aids in even distribution of the force applied while braking or shifting gears. Standard foot of Otto bock is used.

III. EXPERIMENT AND DISCUSSION

The experiment consists of three systems electromyography sensor system, feedback system, remote control system.

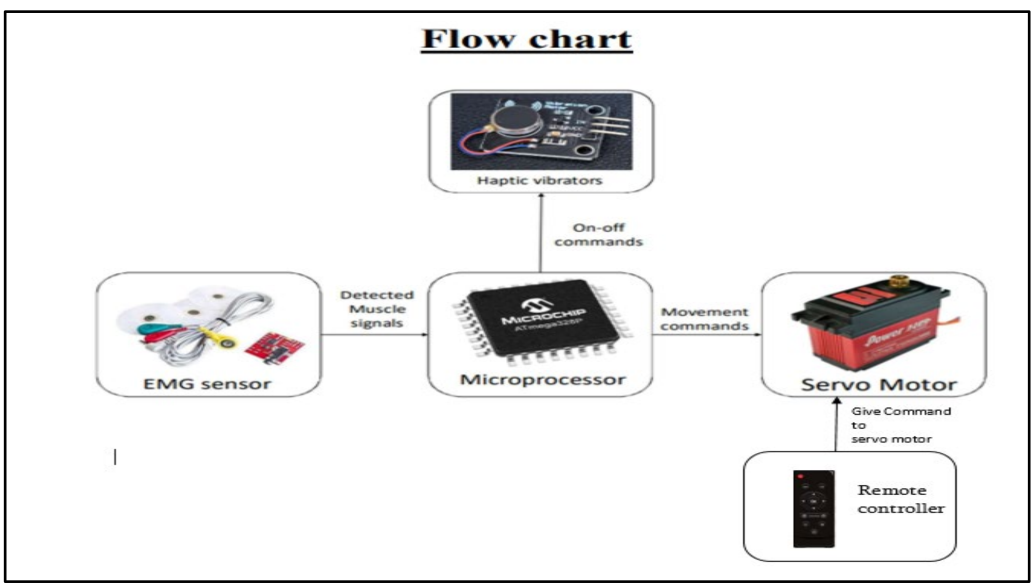

Fig. 3 Integration of various systems and their work flow

A. Electromyography

The Electromyography (EMG) sensor in the project is essential for interfacing to any residual leg muscles that are currently used to control a prosthetic. The EMG sensor is installed efficiently on the residual limb to receive electromyographic signals derived from voluntary muscle contractions. These signals pave the way for intuitive prosthetic control by informing what movement and activity is intended during natural use. The EMG signals are picked up via the electrode array attached to the skin of a limb, and transmitted as electric data that has been read by an EMG sensor before being sent onwards by wire or wirelessly for processing in prosthetic device microcontroller unit (MCU). Sophisticated algorithms in the system's brain (the MCU) then process and read these incoming data, identifying intended user movement. Then servo motor mimics the natural movement of ankles, adjusting its position rotationally and speed-wise based on this analysis. The microcontroller, servo motor and EMG sensor provide smooth and easy control over ankle movement that are distinctive characteristics aiding in significant increase of comfort, functionally ability to move around confidently.

B. Feedback System

A feedback system has been added into the project in order to enhance user experience and provide real-time information of prosthesis movement. Once the ankle has completed its movement, feedback is initiated by the microprocessor. The vibrators, that are integrated into the prosthetic foot itself and begin to vibrate when a signal reaches them from the microprocessor. These vibrations act as kinaesthetic cues to signal that the ankle movement has been completed by a user. This feedback system, users immediately know what the prosthesis is doing and feel more in control of their movements with added confidence. The vibrational feedback supports a greater level of user experience immersion and intuitiveness as well while allowing it to assist in additional synchronization between the user and prosthetic device. The user's quality of life and useable minutes are vastly increased by this feedback system and it allows for higher mobility in terms of coordination.

C. Remote Control System

This project aims to create a control system that will manage the operation of a servo motor responsible for plantarflexion and dorsiflexion with ankle joint from prosthesis. It comes with an easy-to-use system that uses joystick, i.e., wrist watch style detachable device. The device is removable and can easily be attached to any motorcycle handlebar for the convenience of access all through. The remote-control device works by sending wireless user input signals to the receiver module in prosthetic leg. In response to these signals, servo motor is executed at its specified movement [23].

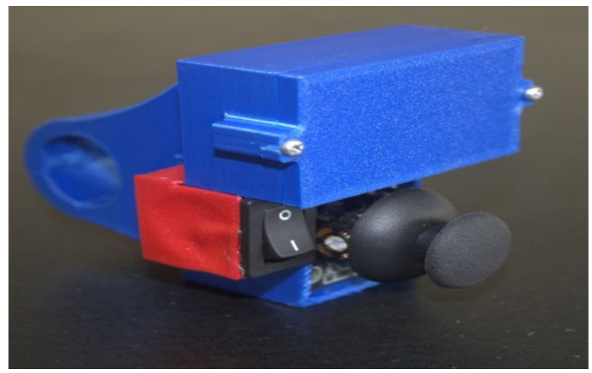

Fig. 4 Remote control system

Fig. 5 Gear testing setup

D. Experimental Work Procedure

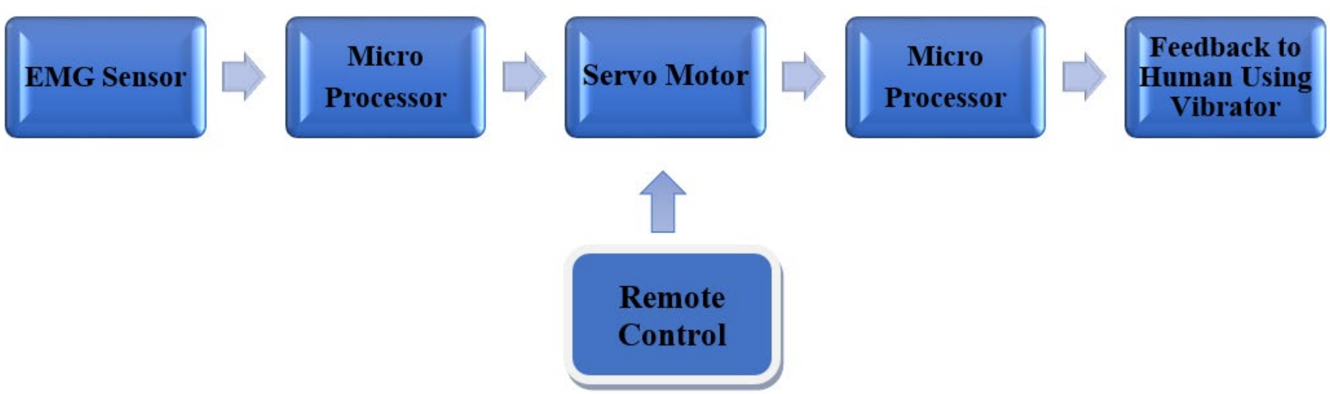

Fig. 6 Experimental work procedure of active prosthetic system

In this project we have used an Electromyography (EMG) sensor so that the prosthetic ankle joint can be used very intuitively. This system operates by sensing electrical impulses out of the muscles in a residual leg, transforming those signals to information and transmitting that info into the microcontroller unit MCU. After MCU logic is initiated, the movement of servo motor attempts to mimic ankle movements. This new approach enhances control and usability, as it permits users to move the prosthetic ankle joint with little muscle contractions.

Moreover, when it is being executed our system has a feedback mechanism for enhancing user experience. These vibrators provide tactile feedback, letting the user know when a motion is complete to make them aware and keep their focus throughout. We also have a method to enable remote control which is available here; remote control. Using a similar technology, users are able to control the servo motor for dorsiflexion and plantarflexion via joystick that is mounted on handle of bike i.e. wrist watch style detachable device. This also allows users to conveniently adjust the mobility of their active ankle joint while riding a motorcycle, thus promoting increased autonomy and use.

IV. RESULTS AND DISCUSSION

The direct objectives of this experimental work method were to increase the functionality, adaptability and ease (ergonomic features) for lower limb amputees that use motorcycle riding as one means of daily transportation. The goal was to design a prosthetic system with both typical ankle motions and feedback mechanisms that can be customized in any different configuration so as to leverage the sense of user experience, safety. A combination of advanced sensor technology, signal processing methods and remote-control capability made it possible.

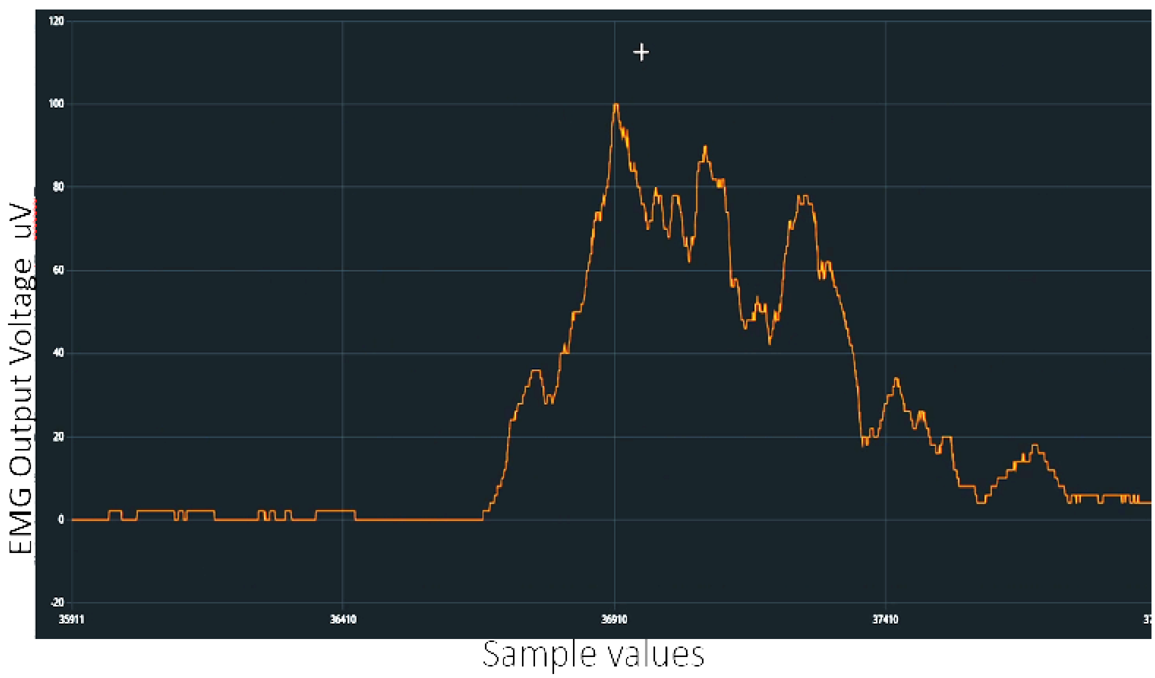

Fig. 7 EMG Threshold value graph (Testing)

Well-Designed experiment on the proposed active prosthesis included a lot of dimensions and it resulted in new information regarding different factors that were involved with movements produced as list below.

1. The new and improved electromyography (EMG) sensors allow seamless integration with the prosthetic limb system, through accurate muscle activity detection & interpretation in-real time. Their accuracy and sensitivity not only made the leg more responsive, but also useful for interpreting even slight movements of muscles as commands.

2. In case of the controlling part, EMG technology was used to track and modify movement parameters as well in real-time for reliability and comfortability during user experience while servo motor control algorithms were optimized for smooth; consistent movements of Prosthetic limb.

3. Vibration signals integrated in the feedback loop give a cleaner input. The vibratory feedback used for movement through prostheses improves user confidence. In addition, haptic feedback technology enabled the translation of tactile signals which brought new control levels and capabilities from user side.

4. According to the tests, a remote- control system works better and add more safety as it is small and detachable so as to be mounted at will on the handlebar of any motorcycle.

5. The servo ankle joint consisted in a prosthetic leg, facilitated for PF and DF (18 degrees) The layout was practical and provided efficient utilization.

V. FUTURE AREAS OF STUDY

1. Future research might focus on the development of signal processing methods and prediction algorithms to enhance adaptive control capabilities in prosthetic limbs, which would be instrumental in increasing commercial success by improving user satisfaction and safety.
2. Future research on user confidence and situational awareness could enhance confidence on a larger scale by exploring different forms of feedback, such as visual or even audio cues.
3. With further advances in miniaturization and sensor technology potentially on the horizon, prosthetic designs could become even less obtrusive for wearers while still providing some level of feedback.
4. The development of new remote-control system designs may benefit from input from ergonomics experts and motorcycle manufacturers, as they could offer useful ideas for design. This would ensure better integration with bike handlebars and enhance user convenience.
5. Long-term clinical trials alongside user studies are required to demonstrate the suitability of prosthetic systems in various lower limb amputee trials and preferences within real-world environments, under different posture transformation circumstances.

VI. CONCLUSION

This paper introduces a solution called “Biomechanical Integration of Active Prosthetic Ankle Movement for Bike Riding,” which represents a breakthrough in assisting lower limb amputees by reducing mobility limitations, particularly in the context of motorcycle riding. This new approach, which focuses on active ankle movement, has led to prosthetic technology that is fundamentally different from previous methods and is deeply aligned with body biomechanics. This innovation allows lower limb prosthesis users to ride in a manner that is far more natural and intuitive than before, greatly improving safety and comfort while ensuring they can participate as equal competitors. A key aspect of this solution is the use of advanced sensor technologies like electromyography (EMG) sensors, which enable remote control. These components work together to allow the prosthetic limb to deliver active, responsive movement that more closely reflects natural ankle behaviour, helping to reduce common issues users experience with current riding systems. Additionally, this solution is versatile and can be adapted for walking to meet daily requirements. It integrates feedback mechanisms like vibration-based signals and haptic technology, providing users with an added sense of security across all activities, addressing mobility needs more comprehensively. Due to its flexibility, this solution is a perfect fit for the varied needs and personal preferences of lower limb amputees, offering both an assistive prosthetic and autonomy in their activities. Overall, this solution represents a significant advancement in prosthetic technology, providing lower limb amputees with an exceptional tool that enhances their freedom of movement, independence, and quality of life.

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