# Electromagnetic Suspension of Lower-Extremity Prostheses

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INTRODUCTION: Despite recent improvements in prosthetic limb technology, over half of patients with lower extremity amputation report dissatisfaction with their prosthesis. While most of the research community has focused on increasing device capability through powered prostheses and advanced controllers, the majority of patient-reported problems relate to shortcomings in device attachment [1]. Conventional attachment methods involve a socket secured around the residual limb using suction or friction between silicone liners and skin, thus suspending the prosthesis from soft tissues. Because soft tissues deform under load, each step during gait causes these tissues to repeatedly stretch and compress about the residual bone. This motion of the prosthesis relative to the bone, known as pistoning, leads to tissue breakdown, sores, and ulceration [2]. The problems caused by soft tissue suspension are so profound that some patients opt for percutaneous osseointegration (OI), in which the prosthesis is attached directly to bone via a titanium rod that protrudes through the skin. This transfers load to the bone without loading the soft tissues, bypassing many of the issues inherent to socket suspension. However, OI also creates a chronic wound that puts patients at perpetual risk of infection [3]. This increased infection risk also makes OI inaccessible to the many patients with amputations secondary to dysvascular reasons or periprosthetic joint infection, which account for over 93% of transfemoral amputations.

As an alternative to these current attachment methods, we propose a new paradigm that transfers load directly to the residual bone (as with OI) via electromagnetics, while maintaining a closed skin envelope. The proposed system (Fig. 1a) consists of a subcutaneous osseointegrated ferromagnetic implant that is attracted by an external electromagnet within the prosthetic socket. The magnetic attraction force between the implant and the electromagnet allow for load transfer across, instead of through, the soft tissues. This paradigm is expected to relieve the soft tissues of suspension loads and greatly reduce pistoning. In the present work, we evaluate the feasibility of a magnetic prosthetic attachment for transfemoral amputations with regards to the system's force production capabilities, the power required during operation, and the amount of heat generated by the magnet.

METHODS: To inform the implant design, multiple cadaveric dissections were conducted to evaluate the overall size and shape of the ferromagnetic implant, and identify any implant features that may aid the surgical process. A biomechanical model based on published gait data [4] was used to calculate the attractive force required to maintain the prosthesis firmly attached to the residual limb during walking. Gradient descent optimization was performed to determine the optimal electromagnet geometry for this implant, based on simulated performance in electromechanical modeling software (JMAG, JSOL, Tokyo, Japan), to meet specific force, mass, and power requirements. The resulting implant and magnet designs were manufactured, and the final device was evaluated on a physical testbench (Fig 2a) capable of simulating the attachment loads experienced during level ground walking. Attractive force as a function of gap distance and electrical current was used to calculate the power required to suspend a knee-ankle-foot prosthesis during walking.

RESULTS: The implant design fits within the closed skin envelope of the residual limb, with an expected soft tissue coverage of 1.5 cm. The implant has a large distal end to facilitate end-bearing. The force required to attach a robotic knee-ankle-foot prosthesis during gait depends on socket mass (Fig. 1b). The optimized electromagnet has a mass of approximately 1 kg and is composed of a permanent magnet core, an electromagnet coil, and a ferromagnetic shell. Thermal simulations showed a nominal temperature increase of 3°C at the skin surface after 1000 continuous steps. The implant and electromagnet were successfully manufactured for benchtop testing. Testbench results showed good agreement with model predictions, with a root mean square error of 4.2% between simulated and measured force (Fig. 2a, b). The average power required to suspend the prosthesis during walking is 32W (Fig. 2c). Direct thermal measurement showed an increase of 2.7ºC during a bout of 200 consecutive steps.

DISCUSSION: This study demonstrates the feasibility of an electromagnetic attachment paradigm for lower-extremity prosthetic limb devices. The physical electromagnet system is capable of producing sufficient attractive force at the expected gap distance to suspend a prosthesis during gait without overheating. In the future, the system will be tested under closed-loop control during dynamic gait-relevant tasks, to ensure robustness in unpredictable disturbance fields. This same concept also has relevance for suspension of upper-extremity prostheses, especially in cases of conical or short residual limbs.

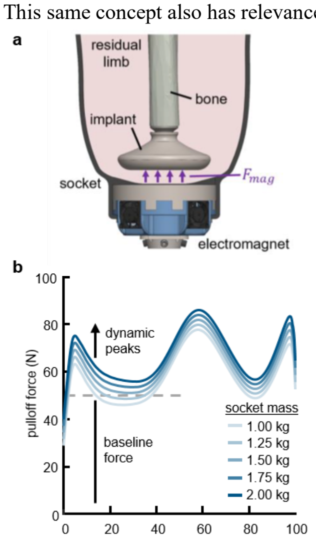


**Figure 1.** Magnetic suspension. (a) The system is composed of a ferromagnetic implant and an external electromagnet. (b) Biomechanical results of socket pulloff force during walking.

SIGNIFICANCE/CLINICAL RELEVANCE: Electromagnetic suspension has the potential to increase the quality of life for amputation patients by improving socket fit and reducing tissue damage. Once translated to the clinic, we expect that this approach will improve overall health, reduce lifetime treatment costs, and restore gait function for persons with transfemoral amputation.

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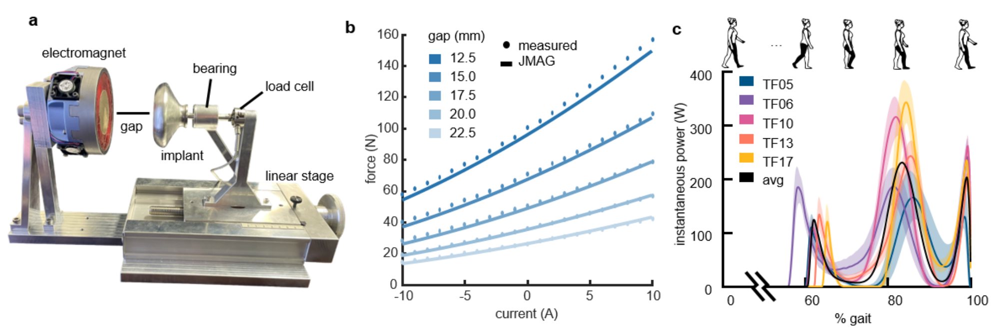


**Figure 2.** Validation of electromagnetic suspension system. (a) Testbench for validating electromagnet performance. (b) Force produced as a function of current through the electromagnet. (c) Electromagnet instantaneous power required to produce the pulloff force during gait. The average power during gait was 32 W.