AN ANIMAL MODEL TO STUDY SKIN-IMPLANT-BONE INTEGRATION AND PROSTHETIC GAIT WITH LIMB PROSTHESES DIRECTLY ATTACHED TO THE RESIDUAL LIMB

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SUMMARY

Despite the number of advantages of bone-anchored prostheses, their use in patients is limited due to the lack of complete skin-implant integration. The objective of the present study was to develop an animal model that would permit both detailed investigations of quality of prosthetic gait and histological analysis of the skin-implant-bone interface after physiological loading of the implant during standing and walking. Full-body mechanics of walking in two cats was recorded before and after implantation of a percutaneous porous titanium pylon into the right tibia and attachment of a prosthesis. The rehabilitation procedures included wearing a cast, controlled increases in implant loading and standing and locomotor training. Detailed histological analysis of bone and skin in-growth into implant was done at the end of the study. The two animals adopted the bone-anchored prosthesis for standing and locomotion, although loads on the prosthetic limb decreased by 22% and 62%. The animals shifted weight to the contralateral side and increased propulsion forces by the contralateral hindlimb. Margins of dynamic stability were generally similar between intact and prosthetic gait. Histological analysis of the implants demonstrated bone and skin in-growth into implant. The developed animal model for studying prosthetic gait and tissue-implant integration demonstrated that a porous titanium implant may permit bone and skin integration and facilitate prosthetic gait. Future studies with this model will help optimize implant properties and prosthesis design.

INTRODUCTION

Bone-anchored (or osseointegrated) limb prostheses have been developed and evaluated in human amputees in several countries. These prostheses are rigidly attached to the bone via a solid titanium implant in the marrow cavity protruding through the skin. Despite the number of advantages of bone-anchored prostheses, their use in many countries, including the US, is limited or prohibited due to the lack of complete skin-implant integration. As a result, amputees with these prostheses have a high skin infection rate (18%), which can lead to implant loosening, revision and/or removal [3,8]. Recent *in vitro* and *in vivo* studies of porous titanium implants have demonstrated the potential for better skin-implant integration and the possibility of developing a robust skin barrier to bacteria and other pathogens [1,5,7].

The objective of the present study was to develop a feline model for evaluating gait with the bone-anchored prostheses attached through porous titanium implants (SBIP by Poly-Orth International, Sharon, MA) [1,5,9]) and for testing skin and bone integration with these implants. This model would permit both detailed histological analyses of the tissue-implant interface after physiological loading of the implant and investigations of prosthetic gait adaptations.

METHODS

All experimental procedures in this study were in agreement with the US Public Health Service Policy on Humane Care and Use of Laboratory Animals and were approved by the Institutional Animal Care and Use Committees of Georgia Institute of Technology and Saint Joseph's Translational Research Institute.

Full-body walking mechanics of two adult purpose bred cats were recorded while they walked across an enclosed walkway with embedded force platforms [6] prior to implantation surgery. After implantation of a porous titanium pylon (5 cm x 0.3-0.5 cm, pore size 40-100 µm, porosity 30-50%) into the tibia medullary cavity [5], a cast was placed on the residual limb to prevent loading of the implant. Starting at week 6, the protruding end of implant was loaded several times a week to promote bone integration [2]. At the end of week 10, the cast was removed and a standing prosthesis (Figure 1A) was attached to the implant. After initial training of approximately a week, the animals started wearing a walking prosthesis (Figure 1B)

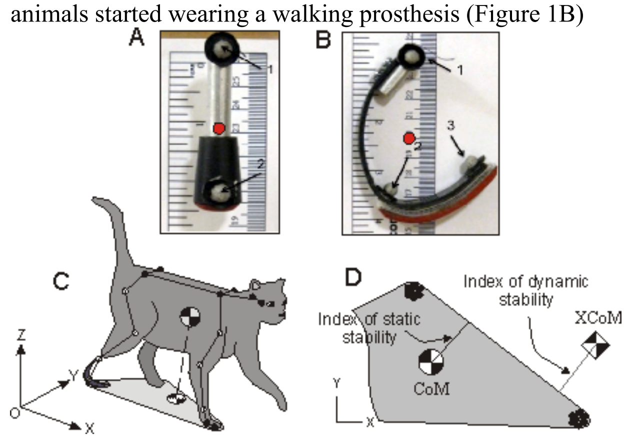

Figure 1: Determining full-body mechanics and stability of prosthetic gait. A, B: Standing and walking prostheses (gray circles indicate marker placement on prostheses, red circles indicate prosthesis center of mass). C: Definition of instantaneous area of support (shaded area between paws and prosthetic foot on the ground). D: Definitions of indices of static and dynamic [4] stability: $XCoM = CoM + V_{CoM}/(\sqrt{g/l})$ is extrapolated center of mass, *CoM* and V_{CoM} are center of mass position and velocity, *g* and *l* are gravitational acceleration and leg length.

continuously. Training lasted for 4-6 weeks until the animals reached stable walking performance. Walking full-body mechanics, including indices of dynamic stability (Figure 1C,D; [4]), were recorded for several weeks. At week 21, the animals were euthanized using deep anesthesia and the limb with implant was harvested for histological analysis [1,5].

RESULTS AND DISCUSSION

The two animals implanted with porous titanium pylons showed no clinical signs of skin or general infection, distress or pain, had normal temperature (range: 35.6 to 37.8 ^{o}C), white blood cells count (range: 9.5-11.0 x 10^3/μL) and appetite (body mass increased after surgery by ~25%). The animals adopted the prostheses for walking within several weeks of training (Figure 2).

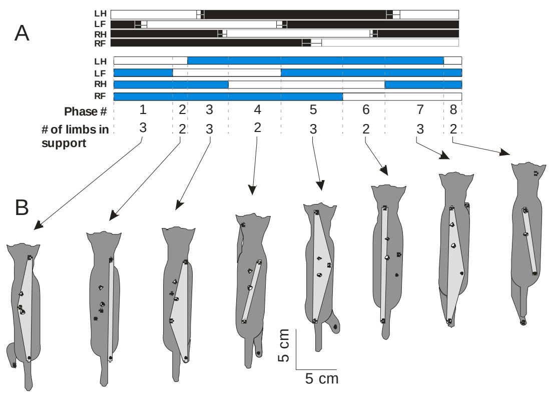

Figure 2: A. Limb support pattern (sequence of phases with different number of limbs on the ground) during intact (black bars) and prosthetic (blue bars) walking of cat 2. Filled bars, stance and unfilled bars, swing; LH, LF, RH, RF are left hindlimb, left forelimb, right (prosthetic) hindlimb and right forelimb. B. Representative base of support areas (light gray area relative to the paws on the ground, CoM and XCoM) for each phase of prosthetic gait of cat 2.

Mean indices of dynamic stability had negative values in several support phases of the cycle (Figure 3), i.e. in these phases XCoM was outside support area (Figures 1C,D & 2B) and the animal was dynamically unstable. The dynamic instability of cat 1 during prosthetic walking increased in phases 2, 4 and 6 (stability indices were more negative than during intact walking, $p<0.05$); however, dynamic stability averaged over the entire cycle slightly but significantly increased for the prosthetic gait. Cat 2 showed no changes in dynamic stability between intact and prosthetic walking for individual phases or the entire cycle (Figure 3, $p>0.05$).

During walking, the animals loaded the prosthesis less than the intact right hindlimb prior to implantation (by 22% and 62% in cats 1 and 2). The vertical loading of the left contralateral hindlimb increased above the forces seen in intact conditions (by 13% and 17% of body weight in two cats). The computed resultant muscle moments at hindlimb joints showed that the prosthetic-limb hip and knee muscle contributions decreased compared to intact conditions. The contralateral hindlimb, conversely, increased hip and knee moments thus providing the necessary forward propulsion.

Bone in-growth was typically noticed in several quadrants of implant histological cross-sections (Figure 4A) with generally more superficial in-growth in proximal parts of implant in both animals. The epidermal layer entered the pores at the skin-implant-bone interface and resulted in skin tissue in-growth into the deeper implant pores (Figure 4B). Skin penetrated the implant to a depth of approximately 0.7 mm.

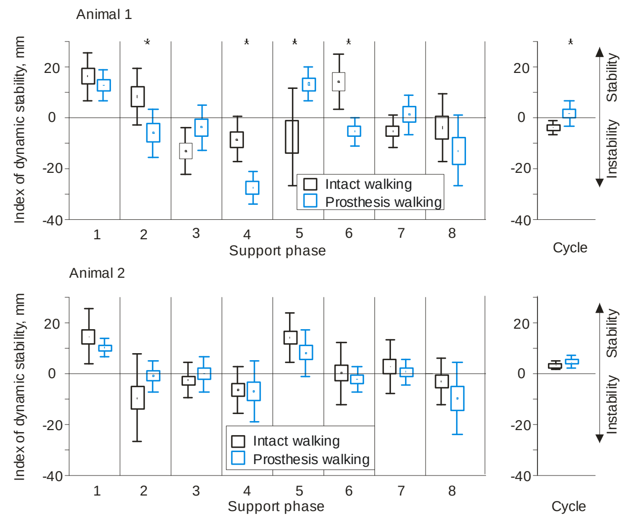

Figure 3: Index of dynamic stability of two animals for each support phase and the entire cycle during intact (black) and prosthetic (blue) gait. *, significant differences between intact and prosthetic conditions ($p < 0.05$). Phase numbers correspond to Figure 2; boxes, ± 1SE; vertical bars, ±1SD.

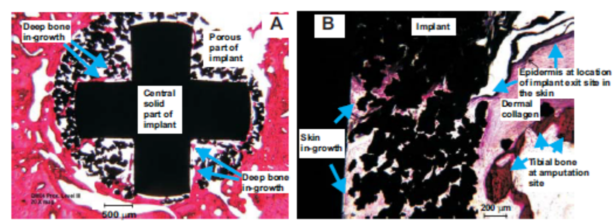

Figure 4: Images of cross- (A) and longitudinal (B) sections through implant, bone and skin of cat 2 (haemotoxylin and eosin stain; 20x magnification).

CONCLUSIONS

The developed animal model to study prosthetic gait and tissue-implant integration demonstrated that a porous titanium implant permits bone and skin integration thus facilitating prosthetic gait. Future studies with this model will help optimize implant properties, prosthesis design and rehabilitation procedures.

ACKNOWLEDGEMENTS

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