A Comparison of Limb-Socket Kinematics of Bone-Bridging and Non-Bone-Bridging Wartime Transtibial Amputations

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Background: While there are proponents of both bone-bridging and non-bone-bridging transtibial amputation techniques, there is a lack of evidence describing functional differences between these two techniques. The goal of the present investigation was to objectively compare the techniques of bone-bridging and non-bone-bridging with respect to limb socket displacement during physiologic loading.

Methods: Fifteen male subjects with an average age of twenty-seven years (range, twenty-two to thirty-two years) who had undergone a unilateral transtibial amputation secondary to a traumatic wartime injury were prospectively evaluated. Seven patients had undergone a bone-bridging amputation, and eight had undergone a non-bone-bridging amputation. Digital fluoroscopic video was used to measure the vertical displacement of the limb within a total-surface-bearing socket with weight-bearing from 0% to 100% of body weight.

Results: There was no difference in limb-socket displacement between amputation techniques with initial loading (12.78 mm for the bone-bridging group, compared with 12.43 mm for the non-bone-bridging group; $p = 0.88$) or with total loading ($p = 0.98$). Similarly, there was no difference between suspension mechanisms in limb-socket displacement with initial loading (12.15 mm for patients with pin lock suspension, compared with 12.98 mm for those with suction sleeve suspension; $p = 0.72$) or with total loading (18.24 mm for patients with pin lock suspension, compared with 21.42 mm for those with suction sleeve suspension, $p = 0.21$).

Conclusions: The current study demonstrated no difference between surgical techniques with respect to bone-socket displacement. These data provide no evidence to support statements that bone-bridging contributes to a more efficient platform in the total-surface-bearing socket.

Level of Evidence: Therapeutic Level III. See Instructions for Authors for a complete description of levels of evidence.

Two different surgical techniques are commonly used for transtibial amputation. One, popularized by Burgess et al., utilizes a long posterior myofasciocutaneous flap to create a durable soft-tissue envelope covering the end of the residual limb[1]. The other, initially described by Ertl, creates a fusion of the distal parts of the tibia and fibula by means of the osteomyoplastic technique and flexible bone graft[2]. Theoretically, the synostosis between the tibia and the fibula creates a more physiologic and stable weight-bearing platform that minimizes pathologic fibular motion, increases dissipation of forces between the socket and the residual limb, and leads to improved function[3]. There is a lack of evidence, due to the difficulty of reproducing objective measures evaluating the complex interaction between the residual limb and the prosthetic socket during weight-bearing, to substantiate this theory. As a result, bone-bridging between the distal parts of the tibia

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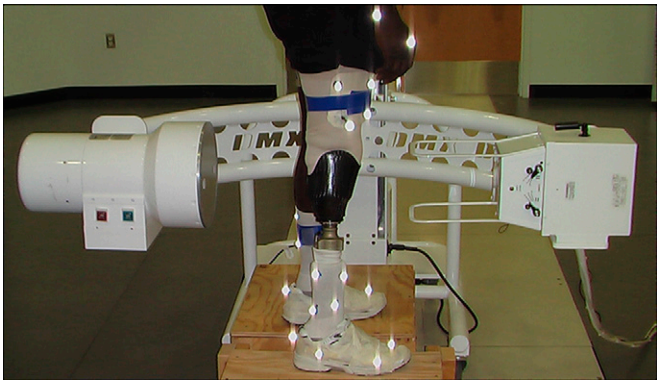

Fig. 1

The subject was positioned with the residual limb within the field of view of the video machine. Anteroposterior images were first made to ensure the appropriate level for imaging, and then the patient turned 90° so that the mediolateral digital fluoroscopic video images could be made.

and fibula remains a controversial technique with both ardent supporters and critics[3 7].

The stability and comfort of the limb-socket interface is a key factor in the overall functionality of a lower-extremity amputee. It is not surprising that vertical motion, or pistoning, of the residual limb within the prosthetic socket has been tied to the development of secondary disabilities in the amputated extremity[8] and that improving the quality of fit can result in significant functional improvement[9]. Unfortunately, the clinical assessment of prosthetic socket fit is primarily dependent on patient feedback and on limited objective assessments such as grease pen markings and physical inspection of the skin and socket liner[9 11]. Other, more advanced modalities such as ultrasound or in-socket sensors provide direct measurement of bone-socket displacement but require specialized sockets and are not feasible for standard clinical practice[12,13].

Digital fluoroscopic video, which has been used to assess joint kinematics[14], holds great potential as a clinically feasible tool for the direct assessment of residual limb-socket interface kinematics. Digital fluoroscopic video can be used to improve our understanding of limb-socket kinematics by accurately and reliably quantifying position and displacement of the residual limb within the prosthetic socket in real time. The goal of the present investigation was to objectively compare the techniques of bone-bridging and non-bone-bridging transtibial amputation with respect to limb-socket displacement during loading within a total-surface-bearing socket with use of digital fluoroscopic video. We hypothesized that neither amputation technique (bone-bridging or non-bone-bridging) would affect vertical displacement between the residual limb and the prosthetic socket during physiologic loading.

Materials and Methods

The present study was conducted under a protocol that was reviewed and approved by our institutional review board and in accordance with good clinical practices. All participants provided written, informed consent prior to participation.

The inclusion criterion for the present study was a unilateral transtibial amputation secondary to a traumatic injury that had been sustained by an otherwise healthy patient while serving on active military duty. Fifteen male patients with a transtibial amputation were recruited, and all of them completed the study. All patients were proficient community ambulators with a minimum of three months of experience walking with their current prosthesis without an assistive device and were fitted with a definitive total surface bearing socket with either suction sleeve or pin lock suspension. Seven patients had undergone a bone bridging amputation, and eight patients had undergone a non bone bridging amputation. The average age of the patients was twenty seven years (range, twenty two to thirty three years). All patients were evaluated prospec tively, independent of the amputation type or suspension mechanism.

Surgical Technique

Skin flaps were fashioned to allow adequate rotation from the posterior aspect of the limb over the distal part of the bone to join the anterior skin in a tension free closure. All attempts were made to fashion skin flaps in this standard fashion without the need for secondary skin coverage. Our patients had trau matic wounds and therefore the skin flaps were occasionally atypical, but tension free closure was still obtained in each case. The tibia was typically

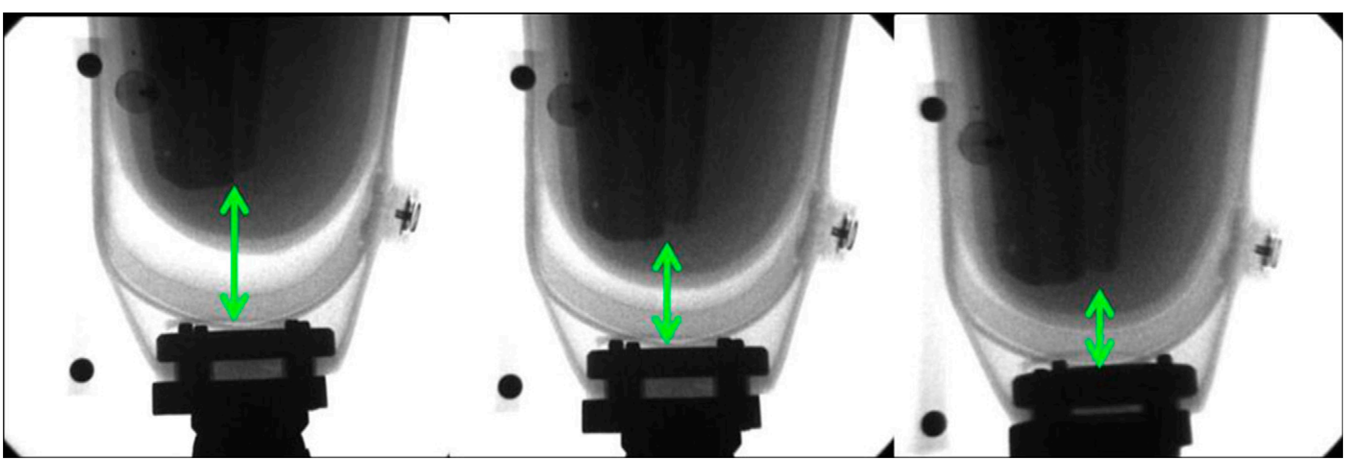

Fig. 2

Sequence of three digital fluoroscopic video images with sequential loading, demonstrating the amount of vertical displacement typically seen with 0% body weight (unloaded) (left), 20% body weight (middle), and 60% body weight (right).

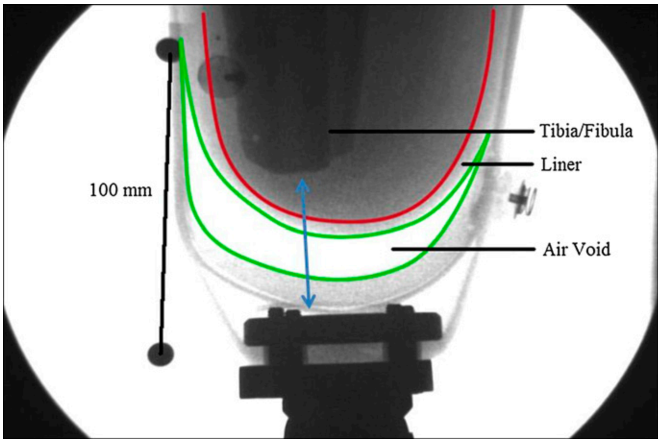

Fig. 3
Lateral fluoroscopic image detailing the areas of interest when socket displacement measurements were made. A standard 100 mm scale was included in all images for standardization. The blue arrow grossly dem onstrates where the displacement measurements were obtained.

divided at the level of the anterior skin incision with a surgical goal of achieving a residual limb length of 12 to 15 cm as measured from the joint line. All patients in the study had a minimum residual limb length of 10 cm.

For those undergoing the bone bridging technique, the tibial perios teum was preserved to help build a reconstructive bone bridge across the distal parts of the tibia and fibula. The periosteum was divided on the anterior and posterior edges of the tibia and was transected distally. A sharp osteotome was used to elevate an osteoperiosteal flap. This flap was a full thickness periosteal flap with small pieces of cortical bone adherent to the flap. A tibial bevel was created to reshape the tibia and to remove the anterior one third of the tibia in all patients. The edges of the tibia were then smoothed and shaped with either a saw blade, a rasp, or a rongeur. For the non bone bridging technique, the fibula is traditionally divided between 1 and 2 cm proximal to the level of the divided tibia. For the bone bridging procedure, however, it is cut approximately 3 cm distal to the cut of the tibia in order to have extra fibular bone available for the bone bridge. The osteotomized fibular bone was then rotated toward the tibia, and a 3.5 mm screw was used to compress the graft between the fibula and the tibia. The tibial osteoperiosteal flap was then sutured in place with absorbable suture. Meticulous attention was paid to the muscular closure. For the standard transtibial amputation, the fascia of the superficial muscular compartment was advanced up and over the end of the tibia to be sewn into the periosteum of the tibia and to the fascia of the anterior compartment. Some surgeons prefer to

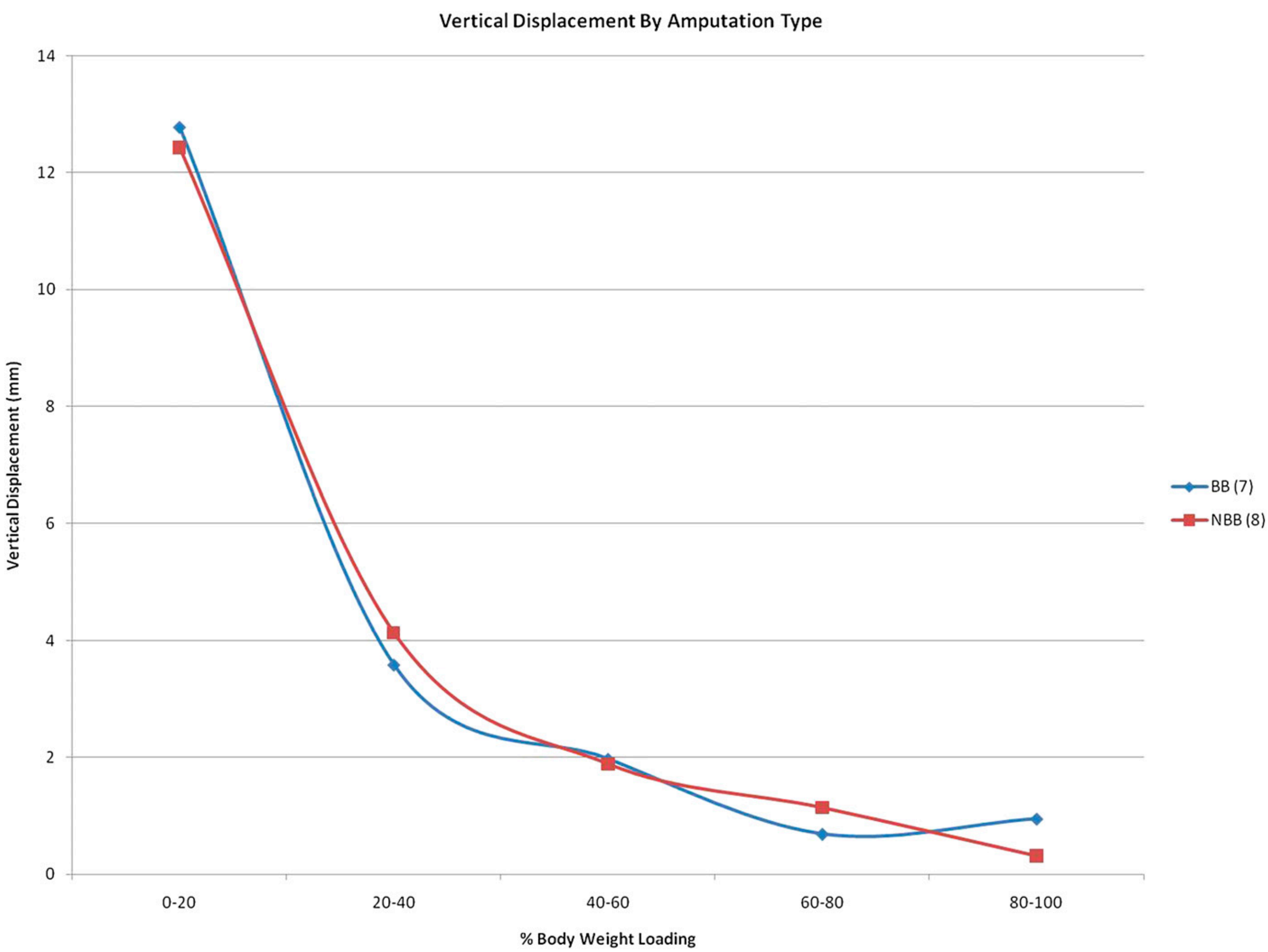

Fig. 4
Line graph comparing vertical displacement with loading between bone bridging and non bone bridging groups. BB = bone bridging, and NBB = non bone bridging.

drill holes in the edges of the tibia just medial and lateral to its crest to secure muscular fascia to the bone. To accurately secure the myodesis, typically three or four sutures were carefully placed under direct vision in the periosteum or through holes in the bone and in the deep and superficial layers of the fascia. The sutures were all placed and clamped and were only tied after the placement of all three or four myodesis sutures. The skin was closed in a tension free fashion.

Prosthetic Fitting

All prostheses were manufactured at a single institution. There was one lead prosthetist who oversaw the manufacturing of the prostheses used by all of the patients who were enrolled in this study. Limb alignment for prosthetic fitting was done with use of the following goals during the patient visit for fitting and alignment, which was typically done at (or just prior to) six weeks after surgery. In the coronal plane, care was taken to ensure that the iliac crests were at the same level, leading to smooth and symmetrical gait with no excessive trunk lean to either side. The foot was typically inset, loading the proximal medial and distal lateral aspects of the residual limb. Socket adduction was typically 5°, with a goal of achieving a vertical pylon or a foot that is flat on the floor at midstance. In the sagittal plane, care was taken to ensure that there was no forced knee flexion or extension during standing and that the shoe had even contact with the floor, with smooth rollover with no knee recurvatum tendency. In the axial plane, the degree of toe out on the prosthesis was made to approximate that of the sound limb and care was taken to ensure that it did not decrease the stability in stance phase[15]. All patients received either pin lock or suction sleeve suspension.

Digital Fluoroscopic Video

The vertical displacement of the residual limb within the prosthetic socket during sequential loading was assessed with use of digital fluoroscopic video. The reliability of using digital fluoroscopic video to evaluate both residual limb position and vertical displacement within the socket has been established previously[16]. Loading of the residual limb was controlled through the use of one AMTI force plate (AMTI, Watertown, Massachusetts) and software allowing auditory and visual feedback indicating that the desired loading parameters were met (BioFeedTrak, Motion Analysis, Santa Rosa, California). Images were collected with use of a digital fluoroscopic video machine (Dynamic Motion X Ray system; VF Works, Palm Harbor, Florida) and were analyzed with use of digital video analysis software (Image Pro Plus, Media Cybernetics, Bethesda, Maryland) (see Appendix) (Fig. 1). Videofluoroscopy uses much less radiation than traditional radiographs, and the total radiation exposure for each patient during the entire study (seventy two images) is equivalent to that associated with a single chest radiograph, which is approximately one fourteenth of the average dose a person receives every year from natural background radiation.

To assess limb socket vertical displacement due to weight bearing, mediolateral digital fluoroscopic video images of the residual limb within the

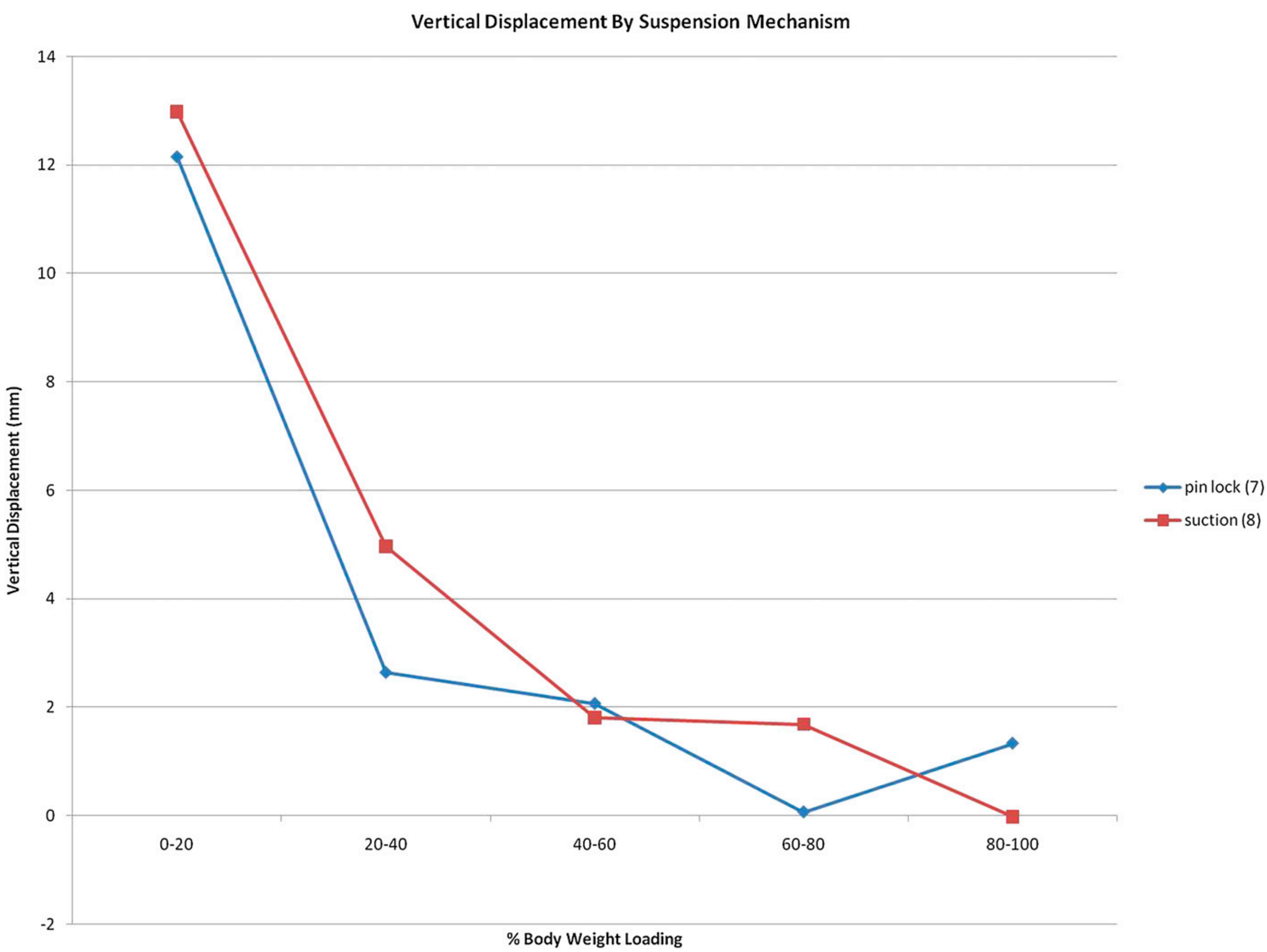

Fig. 5
Line graph comparing vertical displacement with loading between pin lock and suction sleeve groups.

socket were collected as the subject's limb was loaded from 0% to 100% of body weight in 20% body weight increments (Fig. 2). The minimum perpendicular distance between the most distal aspect of the tibia and the superior border of the socket adapter was used to quantify the position of the bone relative to the socket (Fig. 3, blue arrow). Measurements were made during three separate trials, and the average of the three trials was used for data analysis.

Data Analysis

The vertical displacement was calculated between the tibia and the socket for each successive loading interval. Subset analysis was performed on the basis of amputation type (bone bridging or non bone bridging) and suspension mechanism (pin lock or suction sleeve). Mean displacement values for each loading condition were compared between groups. Statistical analysis on initial loading (0% to 20% of body weight) and total loading (0% to 100% of body weight) was performed with use of the Student paired t test with the level of significance set at $\alpha < 0.05$.

Source of Funding

There were no external sources of funding.

Results

Four patients had pin lock suspension and three had suction sleeve suspension in the bone-bridging group, whereas three patients had pin lock suspension and five had suction sleeve suspension in the non-bone-bridging group. Vertical displacement of the bone relative to the socket for initial loading (0% to 20% of body weight) or total loading (0% to 100% of body weight) was not influenced by surgical technique or suspension type.

Comparison of Vertical Displacement with Loading Between Bone-Bridging and Non-Bone-Bridging Groups

There was no difference in vertical displacement with either initial loading (0% to 20% of body weight) or total loading (0% to 100% of body weight) between the bone-bridging and non-bone-bridging groups. The average vertical displacement with initial loading in the bone-bridging and non-bone-bridging groups was 12.78 ± 1.74 mm and 12.43 ± 1.54 mm, respectively (p 0.88). Although the vertical displacement increased by >7 mm with total loading in each group, there was no difference between the groups (p 0.98) (Fig. 4).

Comparison of Vertical Displacement with Loading Between Pin Lock and Suction Sleeve Groups

Further subset analysis was performed between the two types of suspension mechanisms, which also demonstrated no difference in the vertical displacement with both initial loading and total loading. The average vertical displacement with initial loading was 12.15 ± 1.10 mm for those with pin lock suspension and 12.98 ± 1.92 mm for those with suction sleeve suspension (p 0.72). With total loading, the vertical displacement increased to 18.24 ± 1.52 mm for the pin lock group and to 21.42 ± 1.78 mm for the suction sleeve group (p 0.21) (Fig. 5).

Discussion

Proponents of bone-bridging between the distal parts of the tibia and fibula in patients managed with transtibial amputation have suggested that this surgical technique has multiple advantages and have described various indications for its use[5] despite multiple documented procedure-related morbidities, including longer operative and tourniquet times[4]. Most supporters have suggested reserving the technique for younger, active patients who can benefit more from the potentially enhanced function and can tolerate the increased surgical risk[4]. Another widely accepted indication for this technique is for reconstruction of an unstable, painful fibula[5]. The primary theoretical benefit of creating a distal tibial-fibular synostosis is the creation of a more stable soft-tissue envelope with a more functional contour and larger surface area, leading to more efficient dissipation of the load transfer from socket to residual limb[2,3,5,6]. Pinto and Harris described a series of fifteen patients who underwent bone-bridging transtibial amputation and suggested that bone-bridging produced a healthier stump and a better functional result[3]. However, they provided no objective measures or comparison with a non-bone-bridging control group.

In 2006, Pinzur et al. compared a group of thirty-two bone-bridging amputees of various etiologies with a historical control of non-bone-bridging traumatic amputees with use of the Prosthetic Evaluation Questionnaire (PEQ)[5]. Patients who underwent a bone-bridging amputation scored lower (correlating with a worse patient response) than those who underwent a non-bone-bridging transtibial amputation in the Appearance domain but scored higher (correlating with a more positive response) in the Ambulation ($p < 0.05$) and Frustration ($p < 0.001$) domains of the PEQ. Scores were similar between the groups in the other six domains: Perceived Response, Residual Limb Health, Social Burden, Sounds, Utility, and Well-Being. As a result, the authors concluded that the enhanced weight-bearing platform of the bone-bridging technique potentially improved function in comparison with traditional amputation techniques. Although our study did not replicate ambulation, as all study subjects performed controlled weight-bearing of the extremity tested, it did demonstrate that the proposed enhanced weight-bearing platform of the bone-bridging technique did not result in any identifiable difference in terms of vertical displacement within the prosthesis as compared with that associated with non-bone-bridging amputation.

In 2007, Pinzur et al. summarized the controversy surrounding the indirect load transfer to a transosseous amputation via a prosthetic socket. Although a potential benefit of increasing the weight-bearing surface area of a residual limb by creation of a bone bridge, the authors acknowledged that this is an oversimplification of a complex issue[7]. Thus, the improvement in weight-bearing interface kinematics seen with bone-bridging transtibial amputation remains a theoretical argument without objective evaluation to date.

The current study was designed to objectively assess motion at the residual limb bone-socket interface in an attempt to aid the surgeon in choosing the most appropriate transtibial amputation technique. Using digital fluoroscopic video, which allows for direct assessment and quantification of the relationship between the residual limb and the prosthetic socket, we found no effect of amputation type or suspension mechanism on bone-socket kinematics (vertical displacement). This evidence is contrary to the previous argument, which subjectively suggests that bone-bridging may contribute to more comfortable and efficient weight-bearing as a result of the dissipation of weight-bearing over a larger surface area in the total-surface-bearing socket[2,3,5,6]. A post hoc analysis demonstrated that 12,108 patients would be needed to show a difference in overall loading between amputation types (bone-bridging versus non-bone-bridging).

We performed a subset analysis of the effect of suspension mechanism on limb-socket kinematics as an internal control to eliminate this as a potential confounder. In doing so, we demonstrated no difference between the two suspension mechanisms (pin lock and suction sleeve). With an equal distribution of amputation types in each subgroup, the absence of a demonstrable difference based on suspension mechanism helped to ensure that any perceived difference in limb-socket motion was the result of amputation technique alone. We also controlled for subjective functionality differences in our subjects by achieving as homogeneous a patient population as possible on the basis of our inclusion criteria. All of our patients underwent postoperative rehabilitation at the same facility, wore prostheses manufactured by a single prosthetics department, and had similar baseline functionality based on ambulation experience (i.e., ambulating for a minimum of three months with their current prosthesis without the use of an assistive device).

The present study had several limitations. First, the sample size was small. Despite this limitation, the patient population was homogeneous, with minimum variability in the mean displacement values of vertical displacement. In addition, the prosthetic sockets that the patients used in this evaluation are designed to create a total contact fit, which is standard for our amputee population. Although less commonly used today, sockets designed for end weight-bearing may result in a difference in vertical displacement. Even though the prosthetic sockets used by the patients in the present study were designed for a total contact fit, there may have been some element of end-bearing as they progressed to full loading. It would be difficult to confirm this without the use of pressure sensors within the prosthesis. In addition, the forces during gait are different from those experienced by the limb during the testing procedure in the present study. In particular, we did not replicate the anterior and posterior shear forces observed during gait. We did, however, capture the key element of interest, which is pistoning of the limb within the socket during loading. We believe that the surrogate measure of axial displacement during standing approximates the actual displacement of the limb that occurs during walking. Efforts are currently under way to further validate this method. Finally, the results of the present study are based on these objective measurements only and do not take into account functional outcome data.

In conclusion, the present study provides objective data quantifying the residual limb-socket interface kinematics of transtibial amputees during weight-bearing. Our comparison of transtibial amputation techniques revealed no evidence that bone-bridging contributes to a more efficient platform in the total-surface-bearing socket. Therefore, although our results demonstrated no benefit of bone-bridging amputation with regard to vertical displacement within the prosthetic socket with sequential loading, we do not suggest that this technique has no role in clinical practice. The present study does not support the use of the bone-bridging amputation technique solely on the basis of the perception that it can lead to improved residual limb weight-bearing characteristics in patients using modern prostheses. Further research is needed to identify the appropriate patient population that may derive the most benefit from the bone-bridging technique.

Appendix

eA A photograph showing the typical setup in the performance laboratory immediately prior to patient testing and a typical fluoroscopic video used for the acquisition of data are available with the online version of this article as a data supplement at jbjs.org. ■

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