Gait-simulating fatigue loading analysis and sagittal alignment failure of spinal pelvic reconstruction after total sacrectomy: comparison of 3 techniques

Laboratory investigation

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Object. Reconstruction after total sacrectomy is a critical component of malignant sacral tumor resection, permitting early mobilization and maintenance of spinal pelvic alignment. However, implant loosening, graft migration, and instrumentation breakage remain major problems. Traditional techniques have used interiliac femoral allograft, but more modern methods have used fibular or cage struts from the ilium to the L-5 endplate or sacral body replacement with transiliac bars anchored to cages to the L-5 endplate. This study compares the biomechanical stability under gait-simulating fatigue loading of the 3 current methods.

Methods. Total sacrectomy was performed and reconstruction was completed using 3 different constructs in conjunction with posterior spinal screw rod instrumentation from L-3 to pelvis: interiliac femur strut allograft (FSA); L5–iliac cage struts (CSs); and S-1 body replacement expandable cage (EC). Intact lumbar specimens (L3–sacrum) were tested for flexion-extension range of motion (FE-ROM), axial rotation ROM (AX-ROM), and lateral bending ROM (LB-ROM). Each instrumented specimen was compared with its matched intact specimen to generate an ROM ratio. Fatigue testing in compression and flexion was performed using a custom-designed long fusion gait model.

Results. Compared with intact specimen, the FSA FE-ROM ratio was 1.22 ± 0.60, the CS FE-ROM ratio was significantly lower (0.37 ± 0.12, p < 0.001), and EC was lower still (0.29 ± 0.14, p < 0.001; values are expressed as the mean ± SD). The difference between CS and EC in FE-ROM ratio was not significant (p = 0.83). There were no differences in AX-ROM or LB-ROM ratios (p = 0.77 and 0.44, respectively). No failures were noted on fatigue testing of any EC construct (250,000 cycles). This was significantly improved compared with FSA (856 cycles, p < 0.001) and CS (794 cycles, p < 0.001).

Conclusions. The CS and EC appear to be significantly more stable constructs compared with FSA with FE-ROM. The 3 constructs appear to be equal with AX-ROM and LB-ROM. Most importantly, EC appears to be significantly more resistant to fatigue compared with FSA and CS. Reconstruction of the load transfer mechanism to the pelvis via the L-5 endplate appears to be important in maintenance of alignment after total sacrectomy reconstruction.

Abbreviations used in this paper: AX = axial rotation; CS = cage strut; EC = expandable cage; FE = flexion-extension; FSA = femur strut allograft; LB = lateral bending; ROM = range of motion.

This article contains some figures that are displayed in color online but in black-and-white in the print edition.
in axial loading, whereas resection through the S-1 body decreases stability by 50%. Furthermore, resection at S-1 causes a significant decrease in axial rotation (AX) stability. Hugate et al. demonstrated that sacral resection above the S-1 neural foramen resulted in a significant increase in failure rate at normal loads in a biomechanical cadaveric study. Although ambulation is possible without reconstruction after total sacrectomy, reconstruction allows maintenance of height and spinal alignment as well as early mobilization and, thus, avoidance of potential secondary complications related to prolonged bed rest.

The majority of modern reconstruction methods are based on a combination of lower lumbar pedicle screws and transiliac bars to recreate the pelvic ring and the continuity between the lumbar spine and the pelvis. Early techniques used a sacral rod to reconstruct the pelvic ring; however, radiolucency was noted around the iliac screws. The sacral rod has been supplemented with tibial struts and Galveston L-rods to connect the pedicle screws to the iliac screws. One patient treated with this technique demonstrated rod fracture thought to be due to excessive stress on the rod between L-5 and the ilium. Thus the authors modified the technique by adding iliac screws, a transiliac bar, and a larger femur strut. Another modification uses a horizontal cage between the sacral defects. The Galveston rods have also been supplemented with pelvic reconstruction plates between L-5 and the ilium. Others have used bilateral fibular strut grafts placed between the L-5 endplate and the residual ilium to recreate anatomical load transfer from the spine to the pelvis. Titanium cage struts have been placed anteriorly between the inferior L-5 endplate and the iliac portion of the sacroiliac joints bilaterally for the same reason. For larger resections, an expandable cage has been used for vertebral body replacement.

Some of these methods have been subjected to biomechanical testing. However, no studies have evaluated the resistance of reconstruction methods to fatigue, and therefore may not provide a true indication of in vivo performance. With advances in instrumentation, it is likely to be fatigue and not static overload that is driving clinical failures such as implant loosening and breakage.

Current reconstruction methods include femur struts or fibular struts between L-5 and the ilium. The sacral rod has been supplemented with tibial struts and Galveston L-rods to connect the pedicle screws to the iliac screws. One patient treated with this technique demonstrated rod fracture thought to be due to excessive stress on the rod between L-5 and the ilium.

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Current reconstruction methods include femur struts or fibular struts between L-5 and the ilium, and sacral body replacement with cage. The goal of the current study was to evaluate 3 sacral reconstruction methods for stability in range of motion (ROM) and resistance to fatigue. We chose to compare 3 of the most common reconstruction techniques based around the commonly used L3–5 pedicle screws and dual iliac screws, which have been shown to increase stability after total sacrectomy.

Methods

Specimens and Instrumentation

Fifteen L3–pelvis cadaveric specimens were used for the biomechanical analysis. Sacrectomy was performed on all 15 specimens. Pedicle screws were placed from L-3 to L-5 on all specimens. Dual iliac screws were placed bilaterally. Two horizontal bars were placed between the iliac screws and were connected with cross-links. For the femur strut allograft (FSA) reconstruction, an intact femur was sized, cut, placed in an interiliac location, and secured with AO bone screws (Fig. 1A and B; Fig. 2A). For the L5–iliac cage strut (CS) reconstruction, 2 titanium cages were placed obliquely, each wedged between the inferior L-5 endplate and the cut edge of the iliac bone, and secured with AO bone screws (Fig. 1C and D; Fig. 2B and C). For the S-1 body replacement with expandable cage (EC) reconstruction, a rod was placed from the inferior L-5 endplate and locked to the transiliac bar. Over the rod, a 22-mm expandable cage was placed and expanded until it was wedged between the endplate and the transiliac bar (Fig. 1E and F; Fig. 2D and E). Each specimen was randomly assigned to receive 1 of the 3 reconstructions first. After ROM testing, each specimen was rotated through each of the other reconstructions. Each ROM measurement for each reconstruction was directly compared with that same ROM measurement within the same intact specimen to generate an ROM change ratio relative to an intact specimen.

Range of Motion Analysis

Motion-tracking markers were placed to measure the relative motion between L-1 and L-3, L-5 and S-1, and S-1 and pelvis in the intact specimens. Prior to sacrectomy and reconstruction, each of the 15 intact specimens was first analyzed for ROM. Pedicle and iliac screws were placed in each specimen prior to biomechanical testing as described above. Each specimen was driven under a load-controlled pure moment up to 7.5 Nm in flexion-extension (FE), AX, and lateral bending (LB). Nondestructive, multidirectional bending tests were repeatedly conducted on each spinal section in its intact state and following each surgical treatment.

We used a servohydraulic press (MTS Mini Bionix 858, MTS Systems) instrumented with a custom-designed pure moment testing apparatus. Briefly, this apparatus exerts a pure moment via a single cable attached to the hydraulic press actuator. The caudal end of the specimen is rigidly mounted to the base of the hydraulic press, and a cable is wound around a loading ring affixed to the cranial end of the specimen. When the actuator displaces, it applies tension to the cable, which then exerts a pure couple on the specimen via the loading ring. A load cell mounted to the actuator is used to monitor cable tension, and a 3D motion-tracking system (Optotrak 3020, Northern Digital) was used to monitor vertebral displacements and rotations in real time. We used a custom-designed “sliding ring” cable-driven system to induce pure moment loading conditions. This system has been validated in the literature by our group, and has been established to be less error prone than stationary ring configurations.

Nondestructive mechanical tests were performed in all anatomical directions, with preconditioning and final loading protocols based on the spinal section used for the study: 3 cycles of 0 to 1.5 Nm preconditioning at 0.1 Hz and 1 cycle of 0 to 7.5 Nm in 1.5-Nm increments every 45 seconds. Relative vertebral motion was recorded at each loading interval by using the motion analysis system. Specimens were tested sequentially in the following di-
ctions: flexion, extension, right LB, left LB, right axial
torsion, and left axial torsion. The testing apparatus was
reconfigured after each nondestructive test to apply pure
moment loading in a different anatomical direction.

Fatigue Analysis

After each specimen was rotated through the 3 re-
construction techniques and tested for ROM, the last re-
construction for each specimen was subjected to fatigue
testing. The fatigue testing was conducted to simulate
the low-level physiological activity expected during the
early postoperative period following this major surgical
intervention (Stanley, personal communication, 2004).
Compression and flexion activity was simulated with our
custom-designed long fusion gait model (Fig. 3). Com-
pression (300 N), anterior shear (100 N), and flexion mo-
ment (8 Nm) were applied to each of the 15 specimens at
1 Hz for up to 250,000 cycles. The total cycle count for
this protocol was derived from patient rehabilitation pro-
tocols during the early postoperative period (CP Ames,
unpublished data).

During fatigue loading, the slope of the cephalad L-3
endplate was monitored with a goniometer. The slope
at maximum loading every 1000 cycles was compared
with the initial slope. If the change in maximum loading
slope exceeded 20°, the test was stopped and was noted as
failure. The cycle count to failure was recorded for each
specimen. Following fatigue loading, each specimen was
subjected to FE ROM testing to evaluate the stability of
the construct postfatigue. This simulated a significant
change in lower lumbar angulation, which could impact
standing sagittal alignment.

Statistical Analysis

Differences in ROM ratios and number of cycles to
failure (fatigue) were compared by ANOVA. The Tukey
honestly significant difference (HSD) test was used for
post hoc analyses. All analyses were performed using sta-
tistical software (PASW 18.0 Statistics; SPSS, Inc.). Prob-
ability values < 0.05 were considered statistically signifi-
cant. The mean values are expressed ± SD.

Results

Range of Motion Testing

For the intact specimen the FE-ROM was 9.64° ±
3.14°, the AX-ROM was 3.49° ± 2.11°, and the LB-ROM
was 5.78° ± 2.09°. Forty percent of the specimens were
female, and the mean age overall was 76 years. A du-
al-energy x-ray absorptiometry scan was used to assess
bone mineral density in each specimen at the L-4 lev-
el, and demonstrated a mean T-score of 0.5 (range −0.9
to 3.2). Each specimen then underwent sacrectomy and
reconstruction and was subjected to ROM testing. The
FSA demonstrated less stability in FE-ROM compared
with intact specimens (1.22 ± 0.60). In contrast, CS and
EC were significantly more stable compared with intact
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specimens (Fig. 4A; p < 0.001; CS 0.37 ± 0.12; EC 0.29 ± 0.14). The EC was the most stable in AX-ROM compared with intact specimens (0.48 ± 0.70). However, this was not significantly different than FSA or CS (Fig. 4B; p = 0.97; FSA 0.55 ± 0.71; CS 0.70 ± 0.96). Likewise, there were no significant differences between the 3 reconstruction techniques with respect to LB-ROM (Fig. 4C; p = 0.58; EC 0.15 ± 0.26; CS 0.09 ± 0.09; FSA 0.46 ± 1.32).

Fatigue Testing

No failures were detected in the EC group during fatigue testing (Fig. 5; 250,000 cycles). The FSA failed at 856 ± 1067 cycles, a difference that was significant (p < 0.001). The CS was also significantly less resistant to fatigue compared with the EC (794 ± 1186 cycles, p < 0.001). There was no difference between FSA and CS (p = 0.995).

Discussion

Our goal was to directly compare the 3 commonly used reconstruction techniques with respect to stability in ROM and resistance to fatigue. We tested the FSA, CS, and EC methods in cadaveric L3–pelvis specimens. The CS and EC appear to be significantly more stable constructs compared with the FSA in FE. Interestingly, there was no difference in stability in axial rotation or lateral bending. However, the EC appears to be significantly more resistant to fatigue compared with FSA and CS.

Although multiple reconstruction techniques have been used in patients after total sacrectomy, only recently
have several studies been conducted in which biomechanical evaluations of these reconstruction methods were performed in cadaveric specimens. Results of previous studies compare favorably with ours which argues that load transfer from the L-5 endplate to the pelvis is critical to stability.

Murakami et al.\textsuperscript{15} reported a technique based on dual sacral rods that they called the triangular frame technique, which decreased the stress on the spinal rod but appeared to demonstrate increased stress at the sacral rods. Kawahara et al.\textsuperscript{13} biomechanically compared 3 techniques. The authors confirmed high stress between the spine and pelvis in the modified Galveston technique and also high stress at the sacral rods in the triangular frame technique, which may explain loosening in those areas. Furthermore, they reported a new reconstruction method that involved an interface between screws inserted into the L-5 endplate and the sacral rod, which appeared to subject the instrumentation and bones to less stress. Kelly et al.\textsuperscript{14} reported a 4-rod Galveston technique that compared favorably to 2-rod constructs. However, when compared with fibular flap and sacral rod models, the 4-rod model demonstrated the least stability.\textsuperscript{2} This is probably due to the lack of an anterior construct in that model. This is consistent with our findings because the FSA construct, which lacked anterior instrumentation between the ilium and L-5, was the least stable in FE and the least resistant to fatigue compared with EC.

In contrast to previous studies, ours is the first to directly compare an intrailiac FSA method, an L5–iliium titanium CS method, and an S-1 body replacement with a titanium EC from L-5 to the transiliac bar. Furthermore, to our knowledge, this is the first study to evaluate resistance of total sacrectomy reconstruction techniques to fatigue. The major limitation of the current investigation is the fact that it is a study of cadaveric specimens. The L3–pelvis specimens were dissected to preserve ligaments and joints; however, paraspinal muscle forces cannot be studied and, therefore, may not accurately model the in vivo state. Future studies should address the efficacy of reconstruction techniques in patients after total sacrectomy with long-term follow-up, with an emphasis on load transfer from L-5 to the pelvis.

Taken together, our data support the use of S-1 body replacement with an EC after total sacrectomy. In addition to stability in FE and resistance to fatigue, it may optimize spinopelvic alignment postoperatively. When planning reconstruction after total sacrectomy, mainte-
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The assessment of spinopelvic parameters must be considered. Total sacrectomy is one of the few conditions that can cause a change in pelvic incidence, which is critical in defining the amount of lumbar lordosis necessary to maintain sagittal balance. This is potentially important because abnormal pelvic incidence or discordance between pelvic incidence and lumbar lordosis is significantly associated with disability. It is possible that the EC reconstruction may allow for the best maintenance of spinopelvic alignment because, as we demonstrate, it is the most resistant to angular fatigue failure. Of note, however, the EC method should be combined with some method of providing fusion surface between the lateral L-5 endplate around the cage and the inner ilium (autograft, allograft fibular strut, or cancellous graft), because fusion through the cage in this construct is not possible given that the inferior endplate rests on a metal rod.

It is important to emphasize that this biomechanical study analyzed reconstruction methods for stiffness and fatigue resistance. The ultimate goal of reconstruction with instrumentation, however, is formation of a stable iliolumbar fusion. Instrumentation failure after total sacrectomy has been demonstrated in patients who did not achieve bony fusion. It is possible that the EC construct used in conjunction with bone graft may be more likely to result in a solid fusion due to improved immobilization by restricting ROM and resisting fatigue. In clinical practice, structural autograft or allograft fibula or cancellous graft would be placed lateral to the EC between the decorticated L-5 endplate and the pelvis. Future studies will focus on maintenance of spinopelvic alignment after reconstruction with fatigue loading.

Conclusions

Reconstruction after total sacrectomy may allow early mobilization and maintenance of critical spinopelvic measurements. The optimal reconstruction technique is not currently known. The CS and EC appear to be significantly more stable constructs compared with FSA in FE. Most importantly, EC appears to be significantly more resistant to fatigue compared with FSA and CS. Reconstruction of the load transfer mechanism to the pelvis via the L-5 endplate appears to be important in total sacrectomy reconstruction.

Disclosure

Funding and hardware were provided by Stryker. Dr. Ames is a consultant for DePuy, Medtronic, and Stryker. He has direct stock ownership in Visualase, Doctors Research Group, and Baxano Surgery, and he is a patent holder in Fish & Richardson, P.C. He has grants and/or grants pending from Baxano Surgery, and receives royalties from Aesculap and Lanx9. Dr. Deviren is a consultant for NuVasive, Guidepoint, Stryker, and Medtronic. Dr. Buckley received clinical or research support for this study from Stryker Spine.

Author contributions to the study and manuscript preparation include the following. Conception and design: Ames, Leasure, Kondrashov, Buckley, Deviren. Acquisition of data: Ames, Clark, Tang, Ivan. Analysis and interpretation of data: Ames, Clark, Tang, Leasure, Kondrashov, Buckley, Deviren. Drafting the article: Ames, Clark, Leasure, Ivan, Buckley, Deviren. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Ames. Statistical analysis: Ames, Clark, Leasure. Administrative/technical/material support: Ames, Leasure, Kondrashov, Buckley. Study supervision: Ames, Leasure, Buckley, Deviren.

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