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The effect of implant linking and ligament integrity on humeral loading of a convertible total elbow arthroplasty

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Abstract

Background: Both unlinked and linked total elbow arthroplasty (TEA) implants have been employed with no consensus as to the optimal design. The present study aimed to evaluate the effect of collateral ligament integrity and implant linkage on wear-inducing loads in a convertible TEA.

Methods: Eight fresh frozen upper extremities were tested in an elbow motion simulator. A convertible TEA with an instrumented humeral stem was inserted using computer navigation. Elbow kinematics and humeral loading were recorded with the TEA both linked and unlinked. The collateral ligaments were then sectioned and testing was repeated.

Results: In the dependent position, there was no effect of implant linkage or ligament sectioning on humeral loading. Humeral loading was significantly greater following sectioning of the collateral ligaments but not after linking the TEA with the arm in the valgus position. Humeral loading was significantly greater after linking the TEA but not after sectioning of the collateral ligaments and with the arm in the varus position.

Conclusions: Collateral ligament integrity reduces wear-inducing loads for both an unlinked and linked TEA. Linkage of a convertible TEA increases humeral loading, which may have detrimental effects on implant longevity.

Keywords

arthroplasty, biomechanics, constraint, elbow, ligament

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Introduction

Total elbow arthroplasty (TEA) is commonly performed for the management of arthritis, fractures and post-traumatic conditions. While the success rate of elbow arthroplasty continues to improve the optimal design of these devices remains unknown. Both unlinked and linked devices have been employed with no consensus as to the preferred design.

The stability of the elbow is provided by both dynamic and static stabilizers. Dynamic stability is generated by both muscle tone and activation to achieve motion. The static stabilizers are the collateral ligaments and the interlocking shape of the articulation. The importance of ligament repair and osseous reconstruction following fracture or dislocation to restore native elbow stability has been well documented.[1–7] The contribution of the collateral ligaments to stability have been reported for some elbow joint replacements.[8–11] Herren et al.[8] studied the linked GSB III prosthesis and observed that deficiency of the collateral ligaments increased joint laxity. King et al.[11] demonstrated the importance of the collateral ligaments for the stability of the unlinked capitellocondylar arthroplasty. The articular constraint of unlinked elbow arthroplasties has been reported previously, suggesting a wide variation in the intrinsic stability of TEA designs.[12]

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Elbows that have undergone a linked TEA have a third static stabilizer, which is particularly useful in the setting of bone loss, muscle weakness and ligamentous insufficiency. The mechanical linkage connects the humeral and ulnar components, thereby preventing elbow subluxation and dislocation. All currently available linked implants incorporate a 'sloppy-hinge' allowing some varus-valgus and rotational laxity because the loosening rate with constrained hinge devices was unacceptably high.[13]

Although it is generally assumed that unlinked TEA should induce less stress on the implant and hence reduce articular wear and stem loosening relative to linked devices, to date, there are no reported studies that have confirmed this either clinically or experimentally. De Vos et al.[14] reported that linking the Latitude convertible arthroplasty improved valgus stability of the elbow; however, the effect of linking an implant on wear inducing loads is unknown. Furthermore, in the setting of a linked arthroplasty, the importance of preserving or repairing the collateral ligaments has not been established.

The present study aimed to evaluate the effect of the collateral ligament integrity and implant linkage on wear-inducing loads in a convertible TEA.

Materials and methods

Experimental set-up and testing protocol

Eight fresh frozen upper extremities (mean age 73.5 years, range 42 years to 93 years; five male), amputated at mid-humerus with soft tissues intact, were tested in using a computer-controlled elbow motion simulator.[15,16] The motion simulator was equipped with an electromagnetic tracking system ('Flock of Birds'; Ascension Technology Corp., Burlington, VT, USA) with tracking receivers attached to the ulna and radius. The arms were tested in the vertical dependent, varus gravity loaded and valgus gravity loaded orientations in both pronation and supination (Fig. 1). Simulated active elbow flexion was achieved in the vertical orientation using actuators sutured to tendons with muscle loads apportioning based on physiological cross-sectional area and electromyography data. Passive flexion was performed by the operator with the arm in the varus and valgus orientations.

The Latitude® elbow arthroplasty system was employed (Wright Medical, Arlington, TN, USA). This is a convertible TEA that can be used with or without linking the ulnar and humeral components (Fig. 2). The ulnar component was inserted using a modified approach that allowed preservation of the collateral ligaments by employing an olecranon osteotomy. An in-house computer guidance system was employed to align the implants such that the centre and plane of the guiding ridge of the ulnar component was aligned to those of the greater sigmoid notch. A custom humeral stem was designed and fabricated to replicate the commercially available Latitude® humeral component while measuring varus–valgus bending and internal–external torsion across the joint via a custom 2 degrees of freedom load cell (Fig. 2). The humeral component was aligned such that the implant's articulation axis was collinear to the native flexion–extension axis, as defined by the centres of the capitellum and trochlear groove, approximated as a sphere and circle, respectively.[17,18]

The collateral ligaments and native radial head were preserved during humeral and ulnar implantation. The olecranon osteotomy was plated to restore the anatomy of the proximal ulna and function of the triceps. The ulnohumeral kinematics and humeral loading were recorded with the implant in both the linked and unlinked configurations. The medial and lateral collateral ligaments were then sectioned from their humeral origins and the kinematics and loading recorded for both the unlinked and linked configurations.

Statistical analysis

A repeated-measures analysis of variance, with statistical significance set at 0.05, was used to determine the effects of forearm pronation and supination, collateral ligaments, implant linkage, and flexion angle on the kinematics of the elbow and the loading of the humeral implant. The resultant bending load exerted on the humeral stem was calculated by combining (via a summation of the squares) the varus–valgus bending and the internal–external torsion load vectors to produce one net load.

Results

The mean (SD) angular alignment error of the navigation technique for the humeral component was 3.7° (1.1°) varus and 1.4° (3.5°) externally rotated. The positioning error for the humeral component was 1.7 (2.1) mm proximal, 1.5 (1.2) mm anterior and 1.2 (1.4) mm medial. Endosteal abutment of the ulnar stem during placement occurred in six specimens, precluding a precise implantation. The mean angular alignment error for the ulnar component was 7.1° (1.2°) and mean positional errors were 0.5 (1.3) mm, 0.1 (1.4) mm and 0.9 (1.3) mm in the superior, anterior and lateral directions, respectively. Further details of the computer navigation system and the effects of implant malalignment have been reported previously.[19,20]

There were no significant differences in humeral loading or elbow kinematics between pronated and supinated flexion ($p > 0.2$) for any of the combination

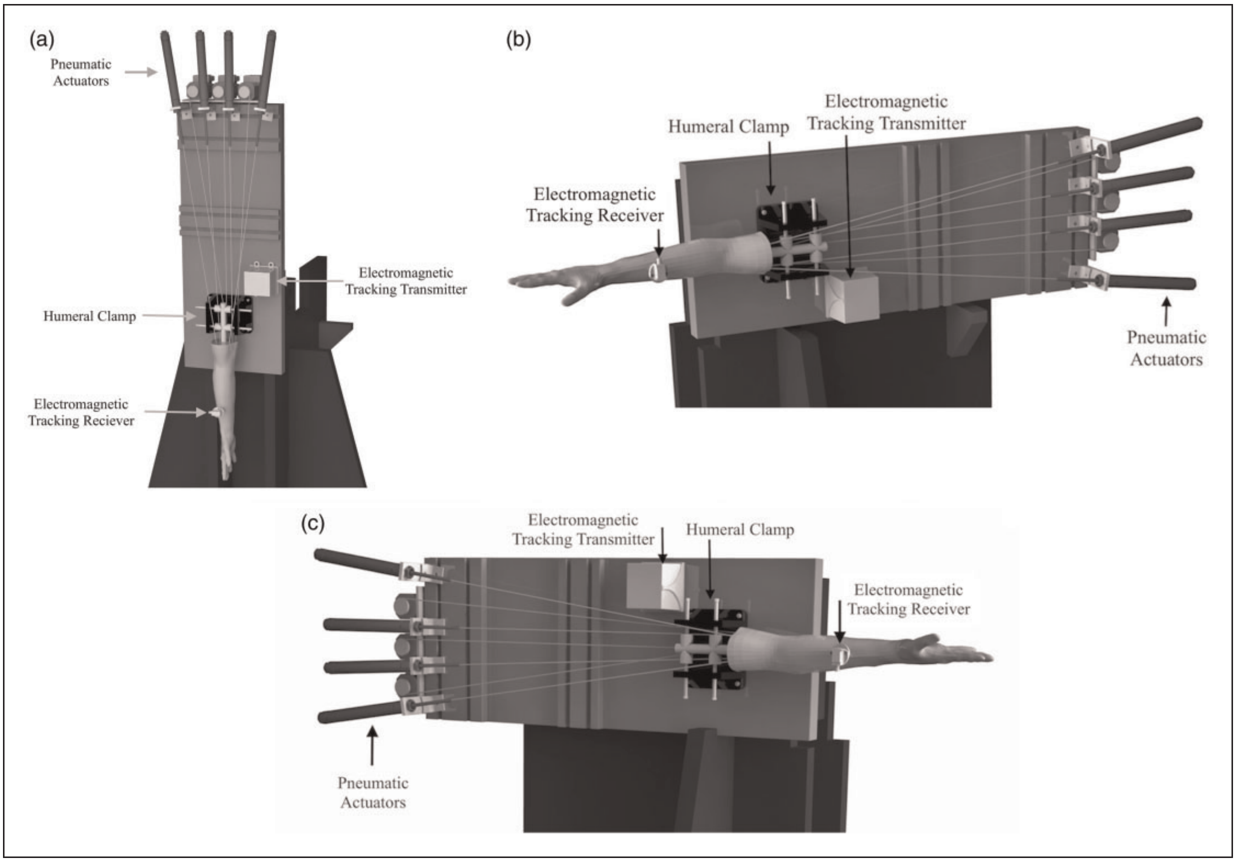

Figure 1. Elbow motion simulator. (a) Dependent orientation. Simulated active flexion was achieved using a computer controlled actuators connected to cables sutured to the biceps, brachialis, and triceps. Elbow kinematics were monitored using an electromagnetic tracking system attached to the ulna. (b) Varus orientation. Passive flexion was achieved by the tester moving the arm. (c) Valgus orientation. Passive flexion was achieved by the tester moving the arm.

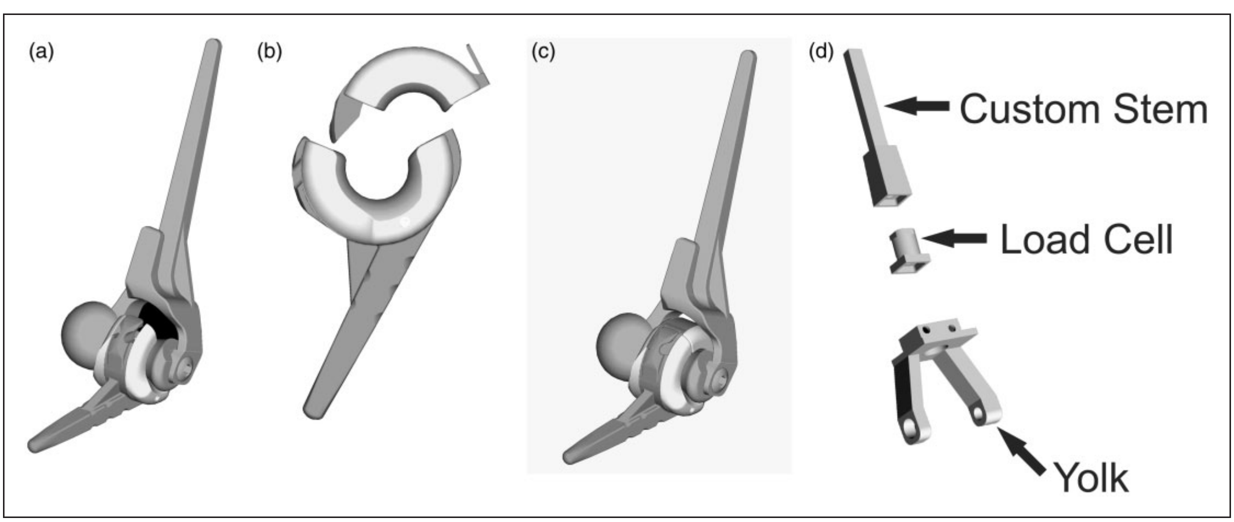

Figure 2. Modified convertible elbow arthroplasty. (a) Unlinked elbow arthroplasty (reproduced with permission from Wright Medical). (b) Linkage mechanism (reproduced with permission from Wright Medical). (c) Linked elbow arthroplasty (reproduced with permission from Wright Medical). (d) Modified humeral component incorporating load cell between stem and yolk.

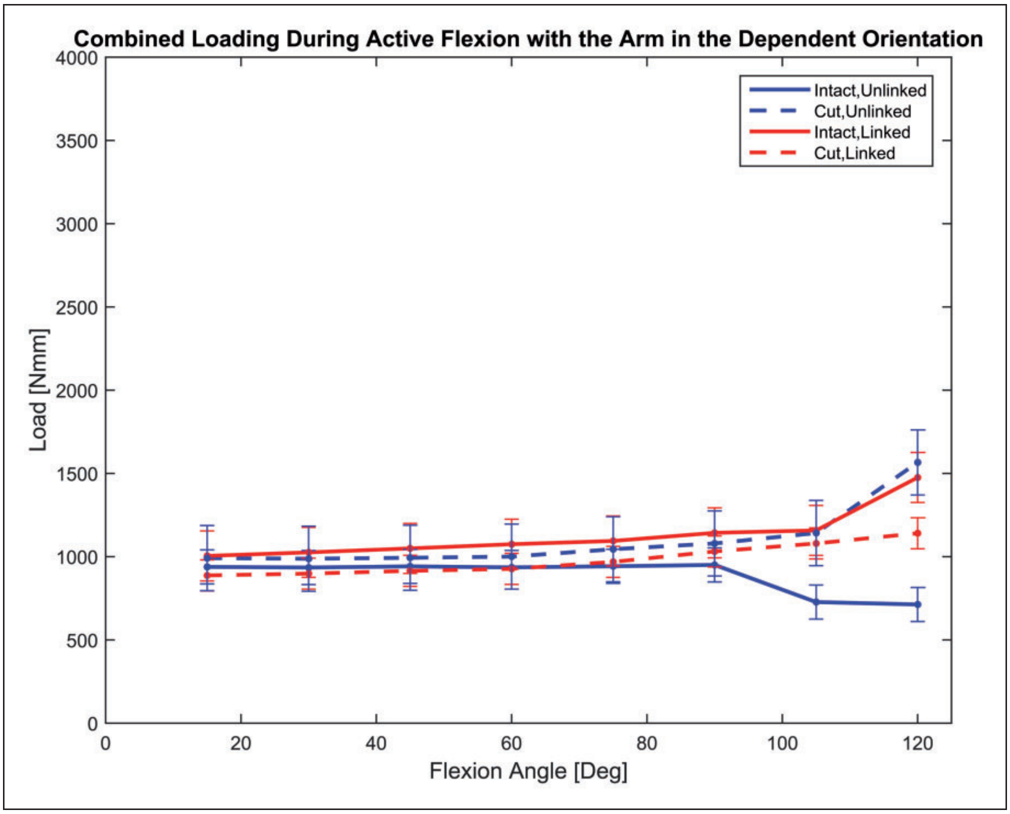

Figure 3. Humeral loading during active flexion with the arm in the dependent position. There was no significant effect of ligament sectioning ($p = 0.77$) or implant linkage ($p = 0.37$) on humeral loading.

of static stabilizers studied; therefore, only supinated data are reported below. The unlinked TEA was highly unstable when tested with the arm in the varus and valgus orientations after sectioning of the collateral ligaments. To prevent the unlinked implants from grossly subluxating or dislocating, the elbow had to be guided by the operator throughout passive flexion. Hence the kinematic data is not reported under passive motion in the varus and valgus positions with the ligaments sectioned.

Dependent orientation

There was no effect of flexion angle on elbow kinematics ($p = 0.79$) or humeral loading ($p = 0.37$); hence, only mean data are reported throughout the arc of simulated active motion. The valgus angulation of the unlinked TEA was 5.4° (5.4°) with the ligaments intact and 4.9° (6.2)° with the ligament sectioned. The valgus angulation of the linked TEA was 5.0° (5.2°) with the ligaments intact and 4.9° (5.7°) with the ligament sectioned. There was no effect of implant linkage ($p = 0.56$) or ligament sectioning ($p = 0.55$) on elbow kinematics.

Humeral loading of the unlinked TEA was 914 (1037) Nmm with the ligaments intact and 1010 (947) Nmm with the ligaments sectioned (Fig. 3). Humeral loading of the linked TEA was 1105 (931) Nmm with the ligaments intact and 1088 (1029) Nmm with the ligaments sectioned. There was no significant effect of ligament sectioning ($p = 0.77$) or implant linkage ($p = 0.37$) on humeral loading.

Valgus orientation

There was no effect of flexion angle on elbow kinematics ($p = 0.49$) or humeral loading ($p = 0.42$); hence, only mean data throughout the arc of passive motion are reported. Gross valgus instability of the unlinked elbows was evident following sectioning of the collateral ligaments. With the collateral ligaments intact, there was a decrease in valgus angulation from 15.2° (6.1°) with the unlinked TEA to 11.4° (3.9°) with the linked TEA; however, this was not significantly different ($p = 0.12$).

Humeral loading of the unlinked TEA was 1020 (534) Nmm with the ligaments intact and 2199 (1394) Nmm with the ligaments sectioned (Fig. 4). Humeral loading of the linked TEA was 2086 (760) Nmm with the ligaments intact and 2463 (1172) Nmm with the ligaments sectioned. Humeral loading was greater following sectioning of the collateral ligaments ($p < 0.0001$).

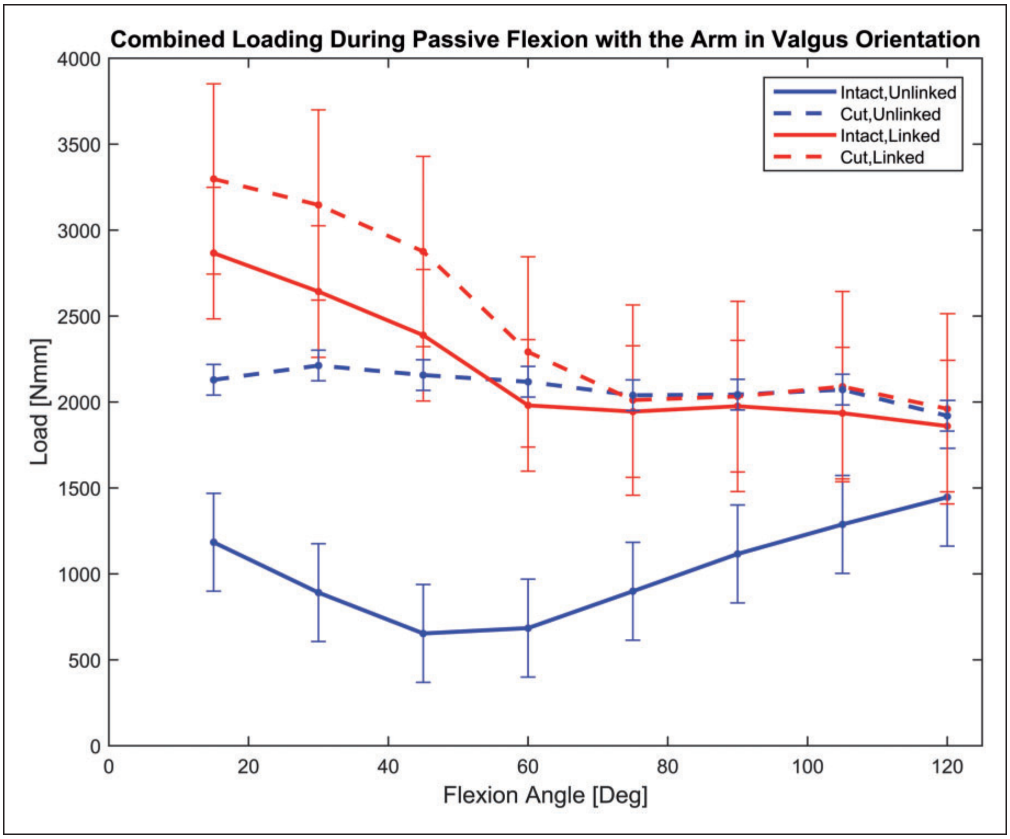

Figure 4. Humeral loading during passive flexion with the arm in the valgus position. Humeral loading was greater following sectioning of the collateral ligaments ($p < 0.0001$). Humeral loading was greater for the linked total elbow arthroplasty, however this was not statistically significant ($p = 0.07$).

Humeral loading was greater for the linked TEA; however, this was not statistically significant ($p = 0.07$).

Varus orientation

There was no effect of flexion angle on elbow kinematics ($p = 0.58$) or humeral loading ($p = 0.54$); hence, only mean data throughout the arc of passive motion are reported. Gross varus instability of the unlinked elbows was evident following sectioning of the collateral ligaments. There was an increase in valgus angulation from −2.1° (5.0°) with the unlinked TEA to 0.1° (4.1°) with the linked TEA with the collateral ligaments intact; however, this was not significantly different ($p = 0.09$).

Humeral loading of the unlinked TEA was 1280 (636) Nmm with the ligaments intact and 1843 (1077) Nmm with the ligaments sectioned (Fig. 5). Humeral loading of the linked TEA was 2055 (852) Nmm with the ligaments intact and 2403 (1072) Nmm with the ligaments sectioned. Humeral loading was greater following sectioning of the collateral ligaments; however, this was not statistically different ($p = 0.11$). Humeral loading was greater for the linked TEA ($p = 0.006$).

Discussion

Unlike hip and knee joint replacement implants where a convergence of design concepts has occurred, TEA systems remain quite variable. Wear and loosening rates of TEA devices are remain concerning, particularly in younger and more active patients.[21–24] To date, unlinked TEA systems have not been shown to be superior to linked implants; however, the design of these devices and indications for surgery have varied, making true comparisons difficult.[22] Also, the role of retaining or repairing the collateral ligaments where possible has not been addressed for linked implants. A convertible TEA design allows the surgeon to choose whether to repair the collateral ligaments or link the device based on the integrity of bone and collateral ligaments, as well as muscular tone. The importance of collateral ligament integrity and implant linkage on wear-inducing loads in a convertible TEA have not been reported.

The resultant humeral loading was similar for simulated active motion with the arm in the dependent position throughout flexion. Although there was a small increase in loading towards terminal flexion, this did not reach statistical significance. Given that the applied

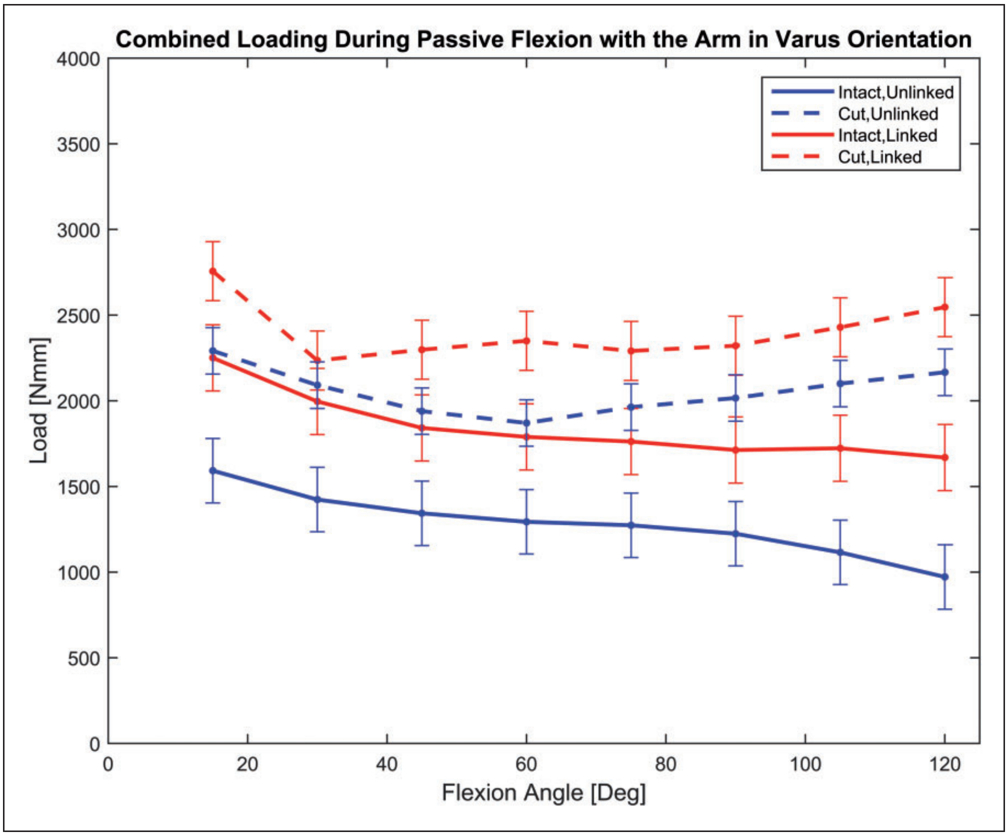

Figure 5. Humeral loading during passive flexion with the arm in the varus position. Humeral loading was greater following sectioning of the collateral ligaments, however this was not statistically different ($p = 0.11$). Humeral loading was greater for the linked total elbow arthroplasty ($p = 0.006$).

loads on the brachialis, biceps and brachioradialis continue to increase throughout flexion as a result of the effects of gravity on the arm, an observed increase in humeral loading was not unexpected. With the arm in the dependent position, the kinematics of the elbow were unaffected by ligament sectioning or linkage of the TEA. This suggests that the simulated muscle forces acting across the elbow apply sufficient compression of the articulation to maintain normal articular tracking. This is consistent with prior data from our laboratory with collateral ligament insufficiency in the native elbow.[25–28] The implant likely did not reach the laxity limits of the ligaments or linkage mechanism with the arm in the dependent orientation as previously reported by Brownhill et al.[19,20]

Humeral loading nearly doubled when the TEA was linked during passive flexion with the arm in both the varus and valgus orientations when the ligaments were intact, reaching statistical significance in the varus orientation. This suggests that the ulnohumeral link likely prevents the collateral ligaments from offloading some of the forces from the implant, resulting in a greater proportion of the loads being passed through the humeral component. Given the common positioning of the arm in the varus orientation with activities of daily living, these data suggest that, in the setting of good bone stock and competent collateral ligaments, the unlinked configuration of this convertible TEA may prove to be more durable in younger and more active patients. To date, however, there is no clinical evidence to support the superiority of the unlinked configuration of the Latitude TEA. Linkage of a convertible TEA increases loading in the humeral stem, which may have detrimental effects on implant longevity as a result of wear and loosening. The linked version of this device is recommended in patients with deficient bone stock, compromised ligaments and reduced muscle function.

After sectioning the collateral ligaments, the unlinked TEA became highly unstable during passive flexion with the arm in both the valgus and varus positions requiring the operator to guide the implant in an effort to prevent dislocation. This was expected because the collateral ligaments are the primary stabilizers of the elbow, as has been previously reported with ligament insufficiency in the native elbow.[29] King et al.[11] also demonstrated the importance of functional collateral ligaments for unlinked TEA in an *in vitro* study. Clinical studies have also reported the challenges of dealing with instability of ligament deficient unlinked TEA.[30] These data support the importance of ligament repair or retention to maintain the stability of the Latitude TEA similar to that reported by Wagener et al.[31]

After sectioning the collateral ligaments, the humeral loads of both the unlinked and linked TEA increased in the varus and valgus orientations, and this was statistically significant with the arm in valgus. This is most likely because the collateral ligaments assist with load transfer. These data suggest that collateral ligament retention or repair, when possible, should be considered when performing both unlinked and linked TEA in higher demand patients.

This *in vitro* cadaveric study was limited by the inability of the elbow simulator employed to generate active elbow motion in the varus and valgus positions. Thus, in some respects, our data represent a worse case scenario with the arm in these provocative positions. It is likely that the addition of muscle loading in the varus and valgus orientations would have resulted in reduced bending loads because the angulation of the forearm would probably have remained more closely aligned to the intended articular plane, thus reducing the engagement of the implant linkage. The increase in humeral loading seen after sectioning of the collateral ligaments in the varus and valgus orientations would likely have been greater if the tester guiding the elbows the elbows had allowed the elbows to dislocate; furthermore, a full arc of elbow motion would not have been possible to achieve. That said, varus arm positioning is common with activities of daily living and so our passive data in this position have direct clinical relevance. The lack of applied loading on the elbow induced by lifting objects in the hand or resisted elbow motions is a further weakness of this investigation. These applied loads would likely have substantially increased the loads seen by the implant, which we consider would further support the importance of collateral ligament retention or repair and the use of the unlinked version of this device in younger and more active patients.

Despite using computer guidance to position the TEA implants, an exact replication of the native axis of elbow motion was not achieved following TEA as a result of endosteal abutment of the implant stems.[18,19] That said the accuracy of implant positioning is likely better than that achieved in clinical practice, particularly in the setting of bone loss and less experienced surgeons. Although these small errors in TEA positioning may have affected the absolute magnitude of the measured resultant humeral loading, the conclusions with respect to the importance of ligament integrity and TEA linkage would probably not have been affected because of the repeated measures experimental design.

The strengths of the present study are the use of image guidance to place the TEA, a novel load cell to quantify humeral loading, the use of a motion simulator to generate active motion with the arm in the dependent orientation and the use of a commonly employed convertible elbow arthroplasty. During unlinked arthroplasty surgery, the collateral ligaments are typically sectioned during implant insertion and repaired to the epicondyles. Although the convertible implant studied allows sutures to be placed through the cannulated axis bolt to improve the security of ligament fixation, healing of the collateral ligaments to the smooth metal of the implant device does not occur. Loading of the humeral component in the early postoperative period would likely be higher with transhumeral implant sutures; however, this would not be expected to persist because load transfer through these sutures will attenuate over time as ligament healing to the epicondyles occurs. We retained the native attachments of the collateral ligaments as a result of the use of a modified surgical approach that incorporated an olecranon osteotomy. The ligament intact condition of the study models the effect of collateral ligament retention or sectioned collateral ligaments that have healed back to their origins on the lateral epicondyles after repair. Thus, we modelled the long-term clinical scenario rather than the perioperative situation of acute ligament sectioning and repair.

The linked version of this device should be considered in patients with compromised ligaments and reduced muscle function; however, the increase in humeral loading with the increase in implant constraint suggests these patients should be cautioned to avoid heavier activities as a result of the greater stress on the implant. The unlinked version of this implant with collateral ligament preservation or repair may be preferred in younger and more active patients where sufficient bone stock and ligament integrity make this an option.

Declaration of Conflicting Interests

The author(s) declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: Graham King is a surgeon designer and consultant for the implant studied in this investigation.

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Ethical review and patient consent

Ethical review and patient consent were not required for this study.

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