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A Pre-Operative Planning Tool for Patient Specific Guide Stability Assessment: An Experimental Validation

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Abstract

This work describes the development and experimental evaluation of a software tool (OrthoGrasp) to predict the stability of patient specific guide (PSG) designs. The tool assists in the design of PSGs to ensure that they will provide the high level of stability required to achieve successful and accurate surgical drilling tasks. OrthoGrasps adapts robotic grasping theory to analyse potential PSG designs by treating each point of contact between the guide and the host bone as a force-torque wrench that can be used to calculate stability metrics. The efficacy of OrthoGrasp was evaluated in this study by conducting a series of force-to-dislocation experiments for a range of glenoid anatomies and associated PSG designs that were analysed using OrthoGrasp. The OrthoGrasp derived Least Resisted Wrench (LRW) and Volume Of the Polytope (VOP) metrics, adapted from the robotic grasping literature were then compared to the experimental results through the use of Spearman Rank Correlation analysis. The results demonstrated that the VOP metric was in good agreement with experimental results and thus could be used to predict the overall stability of a PSG design, but the LRW metric had poorer predictive value. In summary, this work demonstrated the potential of the OrthoGrasp pre-operative planning tool to objectively analyse and rank potential PSG designs to ensure that surgeons are provided with guides that stably fit their patients to assist in achieving optimal surgical accuracy.

1 Introduction

Patient specific guides (PSG's) are a tool used to improve accuracy during orthopedic surgical procedures, by fitting onto one unique part of a bone in a stable configuration that is difficult

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to displace. Currently, PSG's are created using surgeon and engineer expertise to heuristically determine which design will maximize PSG stability and accuracy [3, 4, 1]; however, this process is highly subjective and it is impossible to confirm the PSG's stability prior to fabrication.

Mattheijer et al. develop analytical methods to shape PSG's to obtain high resistance to a large variation of applied forces, but this work was limited to two dimensional cases that could not be practically applied to the clinical setting [2].

To overcome the current subjective process and limitations previous work, we designed a pre-operative planning software (OrthoGrasp) that provides real-time estimates of PSG stability, and conducted an experimental validation of its predictions.

2 Methods

2.1 OrthoGrasp

Robotic grasp analysis is a mathematical method to model, analyze and describe contact forces between actuators and objects. Here, the object is the PSG and the actuators are the surgeon's finger pressing on the PSG and the reaction forces on the PSG from the bone surface. Collectively, the finger and the bone reaction forces form a 'grasp'.

OrthoGrasp (Figure 1) implements two established grasp quality metrics: largest-minimum resisted wrench (LRW) and volume of P (VOP), where P describes the volume of the polytope created by graphing the wrench of each contact load, in which each coordinate is the magnitude of the individual wrench values (i.e. x, y, z forces and moments). The LRW can describe the stability of the least stable direction of loading of the grasp and VOP describes the wrench space volume, which measures overall stability.

Despite each contact wrench being composed of 3 force and 3 moment components, in the context of a PSG application only 3 DOF are meant to be resisted; namely, two forces parallel to the glenoid surface and one torque about the vector normal to the surface. Thus, in this work, the VOP and LRW metrics are reduced to 3 DOF metrics.

In the OrthoGrasp program, a PSG CAD geometry is analysed by identifying the point of contact of the surgeon's finger and all of the points of contact between the PSG and the bone surface. The wrench for each contact point is then calculated and the 3 DOF VOP and LRW metrics are calculated.

2.2 PSG Test Samples

To assess the predictive ability of OrthoGrasp, PSGs were generated based on a commercially available glenoid PSG. Each PSG has four feet that contact the glenoid rim. PSGs were design for six glenoid anatomies, and for each glenoid, three variants of the contact foot placement around the glenoid rim were generated. For each foot placement variant, two types were created with varying levels of foot-to-bone contact by altering the degree to which each foot wrapped around the glenoid rim (denoted as A B type). This yielded 36 different PSGs, which provides sufficient data to identify similarities in trends between the OrthoGrasp predictions and experimental results. Each of these PSGs was analysed in OrthoGrasp and subsequently additively manufactured along with a model of the glenoid geometry.

2.3 Experimental Testing

An experimental testing apparatus (Figure 2) was designed that enabled the PSGs to be docked to and compressed against the glenoid anatomy with a force equal to that applied by a surgeon intra-operatively. Subsequently, a Material Testing System (MTS) translated the PSG in the anterior, posterior, superior, and inferior directions while measuring the required force. As well, force required for clockwise and counter-clockwise rotation around the vector normal to the glenoid surface was measured.

2.4 Data Analysis

Experimental stability data for each PSG was extracted by identifying the highest force value prior to PSG dislocation. To make comparison possible to the OrthoGrasp VOP metric, we created a volume proxy metric for the experimental data of each PSG by summing the force values for each direction-pair (e.g. anterior-to-posterior), and then multiplying the direction-pairs. To make the comparison possible to the OrthoGrasp LRW metric, for each PSG, we determined the minimum percent normalized force/torque value across all six directions.

OrthoGrasp is meant to assess PSG relative stability across multiple designs; thus, in comparing OrthoGrasp data to experimental data, we sought to assess the agreement of stability ranking across the 6 PSGs for each specimen in terms of their overall and minimum stability. This was achieved by performing Spearman rank correlation analysis between OrthoGrasp metrics and the normalized proxy experimental metrics for both the VOP and LRW metrics.

Finally, it was known that the A and B-type PSGs should have different stability due to the differing extent of contact of each foot. Thus, the OrthoGrasp metrics were statistically tested using paired t-tests to determine if the difference could be detected.

3 Results

The OrthoGrasp VOP metric provided a strong average Spearman rank correlation to the experimental results of 0.781, while the LRW metric had a value of -0.638.

Paired t-tests demonstrated that the VOP metrics for the A- vs B-type PSGs were statistically different ($p=0.02$) in agreement with the design intent of these PSGs, but the comparison was not significant for the LRW metric ($p=0.18$).

4 Discussion

This work developed a novel tool (OrthoGrasp) to assess PSG stability and experimentally evaluated its efficacy. The strong Spearman rank correlation results, especially for OrthoGrasp's VOP metric, demonstrate that established robotic grasp metrics can be used to effectively rank PSGs based on their overall relative stability. In addition, the observed statistical difference in the VOP metric between PSGs that were designed to have differing stability further confirms the ability to computationally assess PSG designs. However, determining minimum stability is less effective using the established LRW metric, and other analyses are currently being conducted to determine an improved application-specific metric.

4.1 Conclusion

In summary, this work demonstrated the potential of the OrthoGrasp pre-operative planning tool to objectively analyse and rank potential PSG designs to ensure that surgeons are provided with guides that stably fit their patients to assist in achieving optimal surgical accuracy.

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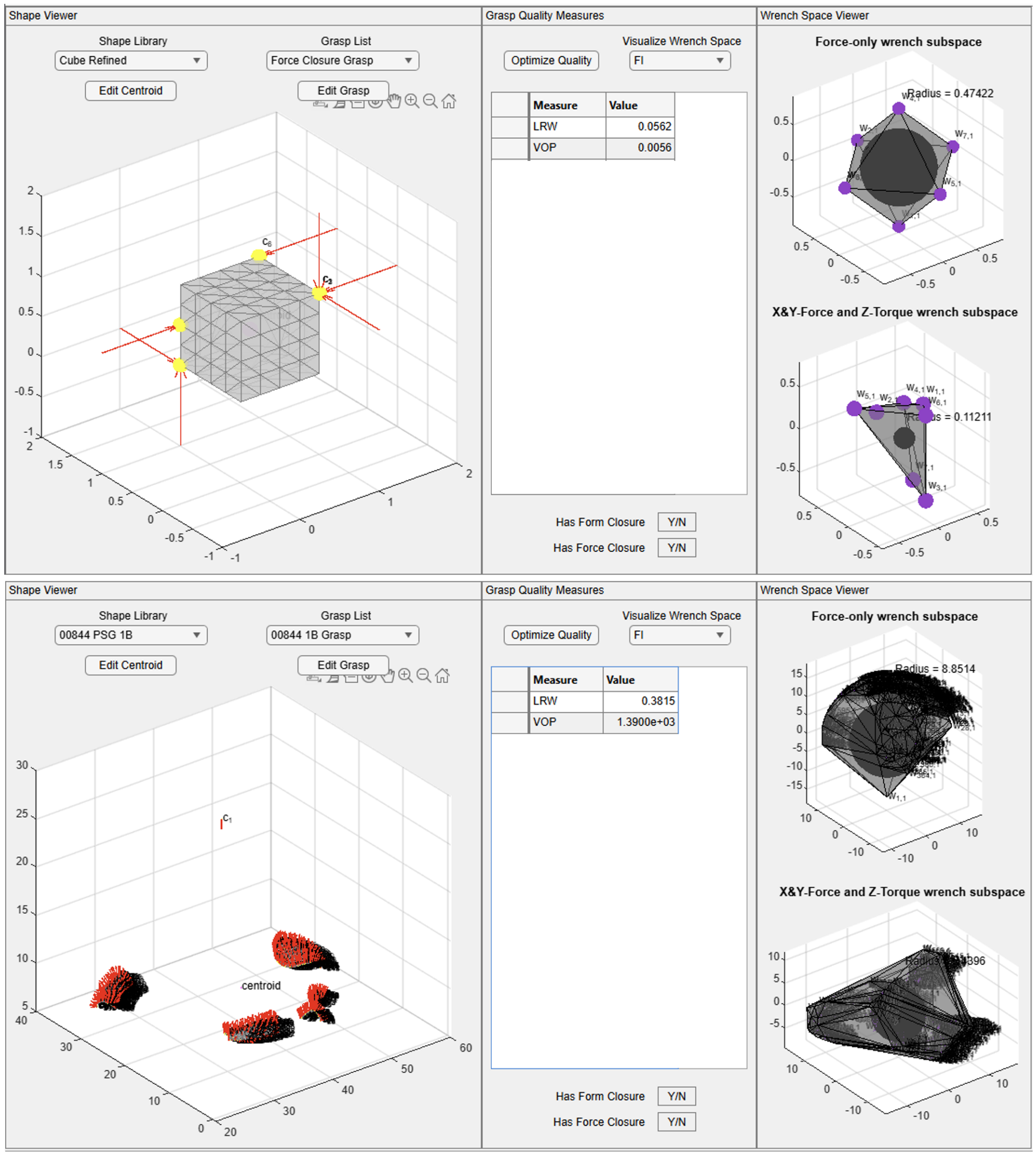

Figure 1: Screen captures of the OrthoGrasp software. Top: demonstration of the software as applied to a simple cube object with 7 contact forces. Bottom: demonstration of the software used with a glenoid PSG, where the PSG body is omitted for clarity to allow visualization of the contacts forces. In each of the images, the left pane shows the object mesh with contact points (yellow spheres) and force vectors (red arrows), middle pane showing the calculated LRW and VOP metrics for the current Grasp of the object, and right pane showing the 3D force sub-space of the overall wrench space in the top graph and the X Y force and Z torque sub-space in the bottom graph.

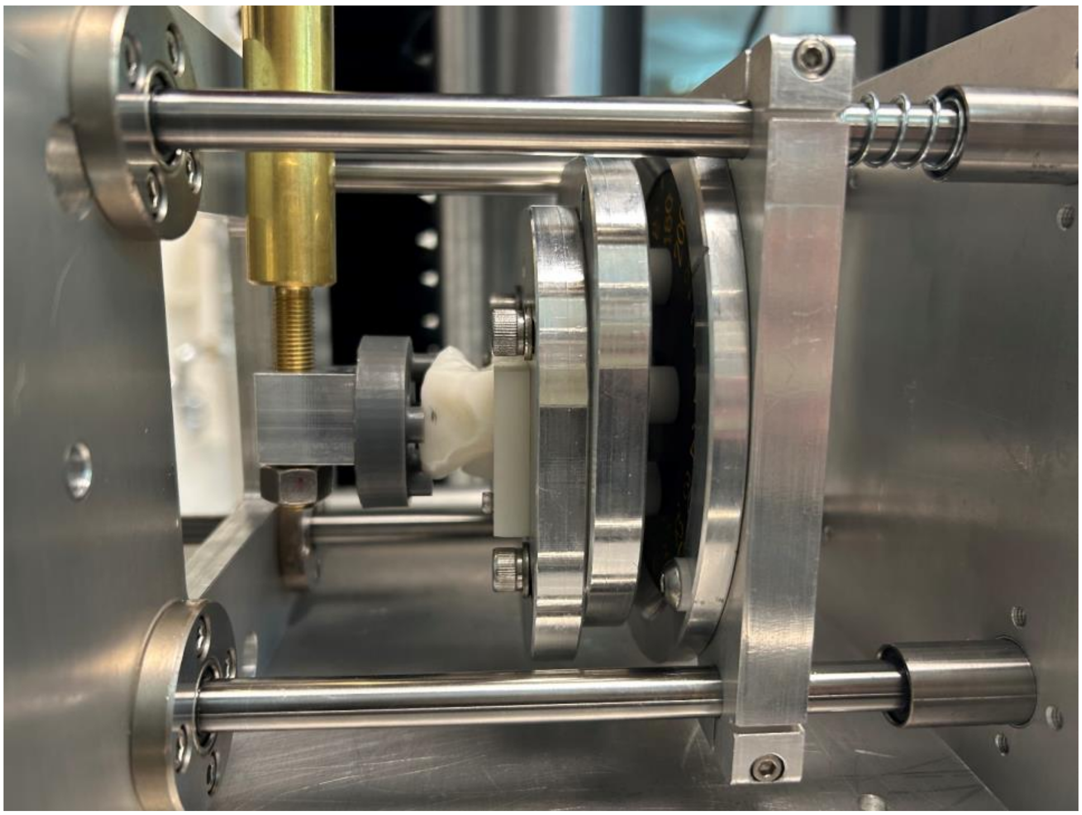

Figure 2: Photo of PSG testing apparatus illustrating the engagement of the PSG with its additively manufactured glenoid model. The PSG is attached to the MTS by a vertical brass shaft while the glenoid model is attached to a low friction horizontal carriage that allows it to be compressed against the PSG using springs to mimic the surgeon's finger force, as well as allowing the glenoid model to shift as the PSG is forcibly dislocated by the MTS.