Evaluation of a Robotic Apparatus for the Analysis of Passive Glenohumeral Joint Kinematics
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INTRODUCTION
The glenohumeral joint has the greatest range of motion in the human body but demonstrates little stability, thereby increasing its susceptibility to excessive translations and consecutive injury. Current models to study shoulder kinematics are subject to limitations since they investigate the glenohumeral joint in isolation without consideration of scapulothoracic motion or the position of the clavicle. In addition, most models depend on manual motion implementation with restricted reproducibility and use discontinuous measurement techniques which both limit the investigation of dynamic motion kinematics. In order to overcome these limitations, we have developed a novel system in which the entire shoulder girdle of a full cadaveric torso is exposed to highly reproducible trajectories created by a robotic actuator. Stereophotogrammetric methods are used for continuous registration of shoulder kinematics. However, the system’s applicability to investigate clinically relevant shoulder kinematics has not been determined yet. Therefore, the goal of this study was to test whether this novel cadaveric system is able to reproducibly capture and discern glenohumeral translations in intact and pathologic conditions.

METHODS
A testing apparatus consisting of a lower and upper frame was designed and manufactured (figure 1). The lower frame moves in X, Y, Z and Z (rotational) directions, while the arm frame moves in the X, Y and Z directions. The axes are moved by actuators and controlled via a central software that can be programmed to generate any motion trajectory. For testing, two anthropometrically different cadaveric torsos were mounted such that the left shoulder of one cadaver and the right shoulder of the other could be tested. Thereby, each torso was secured to a rod fixture connected to the lower frame, the hand was amputated and the wrist was pinned to a robotic actuator of the upper frame. Each shoulder was first subjected to three trials of humeral elevation in the coronal plane prior to and after a cylindrical wedge (24mm height, 50mm diameter) was put under the inferior angle of the scapula to simulate a scapular winging condition. The same motion was repeated after the wedge had been removed. Thereafter, three trials of humeral elevation in the scapular plane were implemented. These three trials were again repeated in each shoulder after the creation of a full thickness supraspinatus tear and after the repair of this rotator cuff tear in a double row technique. During each motion, five high-speed cameras (120 Hz) tracked the motion of passive retro-reflective, bone-embedded marker clusters to simultaneously ascertain the position of calibrated anatomical landmarks of the scapula. The position of these landmarks was used to create a reference coordinate system the scapula and to calculate the center of rotation of the glenohumeral joint for each instant of time as previously described. The trajectories of the glenohumeral center of rotation were described in the scapula reference system with its baseline level taken from the hanging arm position (figure 2).

RESULTS
The trajectories of glenohumeral translations obtained from the same cadaver were highly reproducible for a given condition. The standard deviations (SD) and intraclass correlation coefficients (ICC) calculated from the three sequential trials that were performed for each condition ranged from 0.16mm-0.64mm and from 0.77 to 0.97 respectively. Both ICCs and SDs were not significantly different between the conditions and the two cadavers tested. The system was consistently able to distinguish glenohumeral translations captured in intact shoulders from those recorded in pathologic shoulder conditions. In each axis of the scapula reference system, even small differences between the two conditions (<1mm) were detected (figure 2). Moreover, the system even reproduced in both cadavers the two fundamentally different methods that were used to restore the implemented shoulder pathologies. While the restoration of the scapular winging condition represented a true return to the intact (=baseline) condition, the supraspinatus repair represented another perturbation of the system. Accordingly, we observed a near complete overlap between the trajectories captured at baseline and after the restoration of the scapular winging condition (figure2), while trajectories recorded at baseline and after the supraspinatus repair substantially differed from one another. The reproducibility of a given trajectory in between the two different cadavers was limited. Although some motion patterns of a given condition were repeatable in both cadavers, the absolute X-Y-Z coordinates of a given trajectory substantially differed between the two cadavers.

DISCUSSION
In conclusion, we have demonstrated that the presented passive cadaveric, stereophotogrammetric testing system is capable of differentiating glenohumeral translation trajectories in sequential clinical conditions over a series of repetitions with a high degree of reproducibility. This high test-retest reliability suggests that even small differences in glenohumeral translations observed within a specific cadaver can be directly attributed to the implemented lesions or surgical repairs. However, the system is limited in reproducing the trajectory coordinates of a given condition in between cadavers due to limited force control in this passive cadaveric system and cadaver-specific tissue properties. Nonetheless, the differences between intact and pathologic and restored shoulder conditions may be comparable in between cadavers and subject to paired comparative statistical tests in future studies.

SIGNIFICANCE
The presented cadaveric system will enable for the first time the simulation and investigation of any user-defined dynamic shoulder motion in the entire shoulder girdle and thereby explore the kinematic differences between intact, pathologic and restored shoulder conditions. The results will help to tailor treatment and rehabilitation protocols.