D) Project Description - The biomechanics of anteroinferior shoulder instability - A 3D dynamic analysis

1. Summary

Anteroinferior shoulder instability, often resulting from traumatic dislocation, primarily affects young and active individuals. Recurrent instability remains a challenge, with limited understanding of the interplay between scapulothoracic and glenohumeral kinematics, as well as the role of rotator cuff muscle strength and activation in shoulders which remain unstable despite clinical clearance for return to play. The objective of this study is to advance biomechanical understanding of the impact of muscle strengthening on anterior instability following physical therapy. Utilizing the novel dynamic biplanar radiographic imaging (DBRI) system at Sitem-Insel, this project will allow, for an accurate and high resolution analysis of shoulder joint kinematics and their relation to neuromuscular control. The proposed approach involves using DBRI, electromyography, and musculoskeletal modeling to investigate the contribution of muscle volume and neuromuscular activation in stabilizing the glenohumeral joint during abduction and external rotation motion (ABER). Analyzing dynamic muscular stability in relation to glenohumeral and scapulothoracic kinematics during ABER motion may enhance anteroinferior instability treatment and rehabilitation strategies. The study will involve the analysis of 20 patients with untreated primary anteroinferior shoulder instability, pre and post muscle strengthening therapy. DBRI data will be registered to 3D CT data for 3D dynamic analysis. From the DBRI data, glenohumeral and scapulothoracic kinematics will be analysed and used to drive patient specific musculoskeletal models. Synchronously measured EMG and computed muscle and joint forces will be evaluated in relation to joint stability and shoulder kinematics. Results of this study will be used to optimise the diagnosis and treatment of anteroinferior shoulder instability and help to validate the use of patient specific musculoskeletal modelling for treatment planning and outcome prediction. The study's high-accuracy biomechanical data will further be used to drive force-driven kinematic computational models for patient-specific dynamic analysis of shoulder instability to allow comprehensive clinical diagnosis without the need for radiating imaging in the future.

2. Introduction & current state of research

The shoulder joint offers more freedom of motion than any joint in the body, but it is also the most frequently dislocated [1][2]. Shoulder instability, characterised by shoulder dislocation, shoulder pain and stiffness, bone deformity and loss of function, is a debilitating condition that most commonly affects a young active population [3][2]. Traumatic anterior-inferior glenohumeral dislocation constitutes over 95% of all dislocations [4], impacting 2% of the general population over a lifetime [5]. Short term recurring instability also presents a significant issue with more than two thirds of affected young athletes experiencing recurrent events within a year [6].

Physical therapy of primary instability is a first line therapy that aims to improve stability and reduce symptoms by increasing the muscular contribution to glenohumeral stability through muscle strengthening [7] [8]. Because of the limited ossesus constraint and capsular laxity of the shoulder joint, which is often worsened due to trauma to the capsule, glenoid rim, and humeral head during traumatic dislocation, the shoulder relies greatly on neuromuscular function for stabilization [9][1]. Electromyographic (EMG) study of healthy subjects has shown that activation of the rotator cuff muscles is particularly important for stabilizing the shoulder joint, especially during forced translation of the humeral head within he glenoid fossa [10]. The apprehension position, characterized by 90 degrees of shoulder abduction and external rotation (ABER), is a vulnerable position for the shoulder, in which anterior glenohumeral dislocation often occurs. Placing the arm in the apprehension position is a diagnostic test for shoulder instability, as it commonly reproduces symptoms [11] and elicits fear of dislocation. Ernstbrunner et al. conducted a study using static open CT measurements, revealing the significance of scapulothoracic kinematics in addition to glenohumeral joint motion in this position [12]. Patients with anterior instability mobilized their scapula less than control patients, suggesting altered neuromuscular control. Despite this knowledge, the relationship between scapulothoracic and glenohumeral kinematics, muscular activation, and their role in recurring anterior shoulder instability remains unclear. Recurrence rates of 50% to 75% after return to play from non-surgical treatment of primary anterior dislocations [13] emphasize the need for further biomechanical exploration and understanding of the impact of muscle strengthening on anterior instability. However, dynamic shoulder imaging limitations have hindered precise study of shoulder kinematics and simultaneous muscular control in the past.

Novel dynamic biplanar radiographic imaging (DBRI) systems, such as the system installed at the Dynamic Imaging Center at Sitem-Insel, acquire high accuracy 3D dynamic “video” images during motion, which enables study of glenohumeral kinematics with high spatial accuracy and temporal resolution. The systems acquire radiographic images in two planes which are registered to bone models reconstructed from segmented CT images to obtain the 6 degrees of freedom (DoF) pose of each bone during motion. Relative to implanted tantalum beads, Bey et al. determined the accuracy of DBRI at calculating the dynamic pose of the scapular and humerus in any one direction to be 0.130 mm and 0.095 mm (0.25 degrees and 0.47 degrees) respectively [14]. General methods for measuring 6D in-vivo shoulder kinematics using state of the art DBRI systems have been recently reported [15], and preliminary studies of glenohumeral kinematics of rotator cuff tear (RCT) patients during abduction have been conducted [16]. However only a handful of systems have been installed worldwide and no studies of glenohumeral translations in anteroinferior instability patients or shoulder kinematics during the ABER sequence in general have yet been reported. This study proposes a novel exploration of glenohumeral biomechanics of anterior instability patients using high accuracy state of the art DBRI, synchronised EMG and customized patient-specific musculoskeletal modelling (AnyBody Technology A/S, Aalborg, Denmark) before and after muscle strengthening therapy. The study aims to improve understanding of the role of neuromuscular activation in stabilisation of the glenohumeral joint during ABER motion into the apprehension position in specific relation to glenohumeral translation and scapular rotation.

3. Innovation and translation potential

Results of this study have strong potential for clinical translation. This project represents the first biomechanical study of shoulder instability using state of the art DBRI. Studying the role of dynamic muscular stability in relation to glenohumeral and scapulothoracic kinematics during ABER motion could help to improve the treatment of anteroinferior instability and help to optimise rehabilitation strategies to reduce time to return to activity and rates of recurrence.

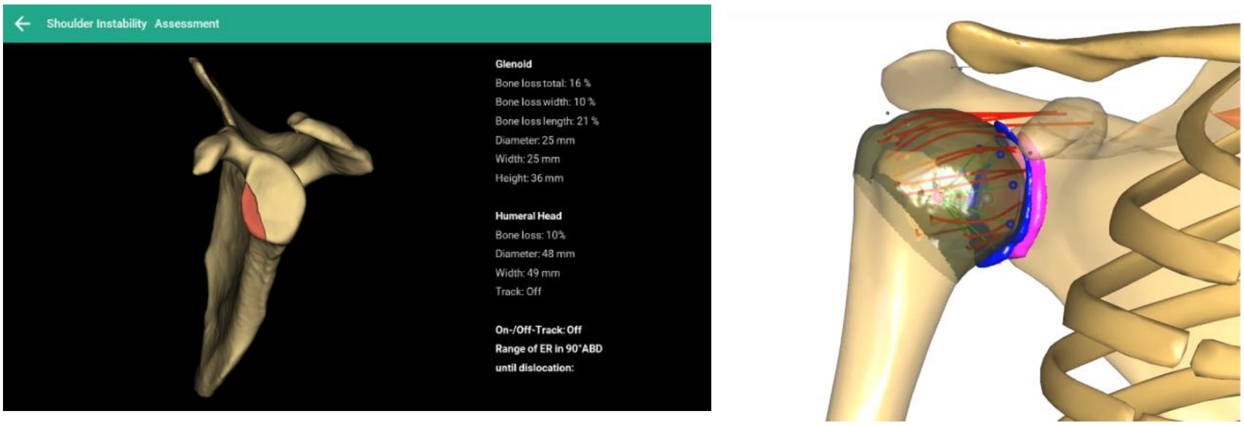

Figure 1. Software application for the diagnosis of shoulder instability (left) and the developed musculoskeletal model allowing evaluation of glenohumeral translations for future comprehensive patient specific diagnosis

Precise assessment of recurrence risk following non-surgical treatment requires evaluation of shoulder kinematics and dynamic stability including muscle activation. However, there is currently no defined method for conducting this assessment in a clinical setting. In a related project, we are developing the first web-based software application for the automated diagnosis of shoulder instability (Figure 1, left). The software will enable automated 3D evaluation of bone loss from CT or MR images, a 3D dynamic analysis of risk of lesion engagement and simulation of the patients’ muscle forces and instability ratio defined as the ratio of shear to compression force [17]. The high accuracy synchronised biomechanical data (glenohumeral and scapulothoracic kinematics, EMG and computed muscle forces during ABER motion) resulting from this proposed study will help to validate these automated calculations of shoulder stability. The study will also be used to validate the potential use of biomechanical models customised to the patients’ anatomy and driven by DBRI kinematic data, for use in clinical diagnosis and treatment planning. The acquired DBRI data and analysis results will also be used for the development and validation of force driven kinematic computational models (Figure 1, right) [18] that will facilitate efficient patient specific dynamic analysis of shoulder instability without the need for 3D dynamic imaging in the future.

4. Project Plan

Study Objectives

The primary objective of this project is to study biomechanics of the unstable shoulder with high accuracy and resolution during ABER motion. We aim to study the relationship between muscular activation, scapular rotation and glenohumeral kinematics in anteroinferior instability patients 1) following primary dislocation and 2) following non-surgical muscle strengthening therapy. We hypothesize that an increase in muscle volume from physical therapy, particularly of the rotator cuff muscles will correlate with reduced glenohumeral translations and reduced apprehension during ABER.

Methods

Patient population

With ethical approval, 20 consecutive patients over the age of 16, presenting with untreated traumatic anteroinferior shoulder instability with positive apprehension test will be prospectively enrolled in this study. Patients who have undergone previous surgical treatment on the affected shoulder or who have hyperlaxity, rotator cuff tear, or unhealthy contralateral shoulder will be excluded from the study. As part of the standard clinical workup, patients will undergo CT of both shoulders and MRI (including 2-pt Dixon MRI with full scapula view) imaging of the affected shoulders. Additionally, an MRI of the healthy shoulder will be acquired. Patients will undergo DBRI with study of both shoulders before and after completing a course of standard physical therapy (12 weeks). A post therapy MRI of the affected shoulder will be acquired to assess muscle volume changes. The patients' Instability Severity Index Score, and Apprehension Test results pre- and post- therapy will also be recorded.

Dynamic Biplanar Radiographic Imaging

The Dynamic Imaging Center at Sitem-Insel Bern (Imaging Systems and Services Inc., Painesville, USA) (Figure 2) allows synchronized 6 DoF DIC-DBRI X-ray imaging in two planes (frame rate 150Hz, 1ms pulse width radiation), skin marker-based motion capture (extended Heidelberg marker protocol[19]) and EMG measurements of the biceps brachii, anterior, middle, and posterior parts of the deltoid, clavicular part of the pectoralis major, latissimus dorsi, and upper trapezius muscles using surface electrodes and the deeper rotator cuff muscles supraspinatus, infraspinatus, and subscapularis, using fine-wire intramuscular electrodes. Patients will execute a prescribed 7 second motion sequence for each side: 1) 0° to 90° coronal plane abduction (1s). 2) 0° to 90° elbow flexion. (1s) 3) Two successive repetitions of progressive humeral external rotation, 0° to maximum range of motion (ROM) (1s), then return to neutral rotation (1s). 4) Return to initial position, extending the elbow, and return to 0° abduction (1s) (estimated radiation dose at 50 Hz of ≤ 4 mSv bilaterally based on dosage reported by Kane et al [16])). A metronome will be employed to help patients keep time. 6 DoF kinematics of each bone (including the scapula, humerus) will be generated using a commercially available 2D-3D markerless bone tracking software (DSX software suite, C-Motion Inc., USA) (Figure 3)previously verified to have a dynamic tracking accuracy of <0.4 mm; <0.25° and <0.5° for the scapula and humerus, respectively.[14] The resulting kinematics will be compared over the whole ROM between the healthy contralateral- and the injured- side using statistical parametric mapping (SPM). During the motion,

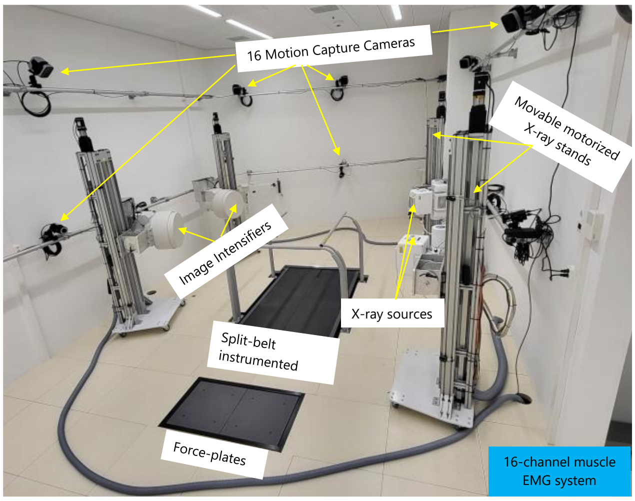

Figure 2. The dynamic biplanar radiographic imaging system at the Dynamic Imaging Center

glenohumeral distance, defined for each of the centroids of the triangles of the surface meshes of the glenoid surface and humeral head based on the method described by Anderst et al. [20] (applied to the shoulder); as well as the path of the contact point of the humeral head in the glenoid, similar to the method described by Miller et al.[21] will be computed. Glenohumeral translations will be calculated relative to the glenoid coordinate system based on a best-fit plane to the glenoid rim, as described by de Wilde et al. [22]. Additionally, we will employ a metric previously utilized by Lädermann et al. to quantify the instability termed "subluxation" [23], (the ratio between the translation of the humeral head center and the radius of the glenoid, subluxation defined as >50%) [24] (Table 1).

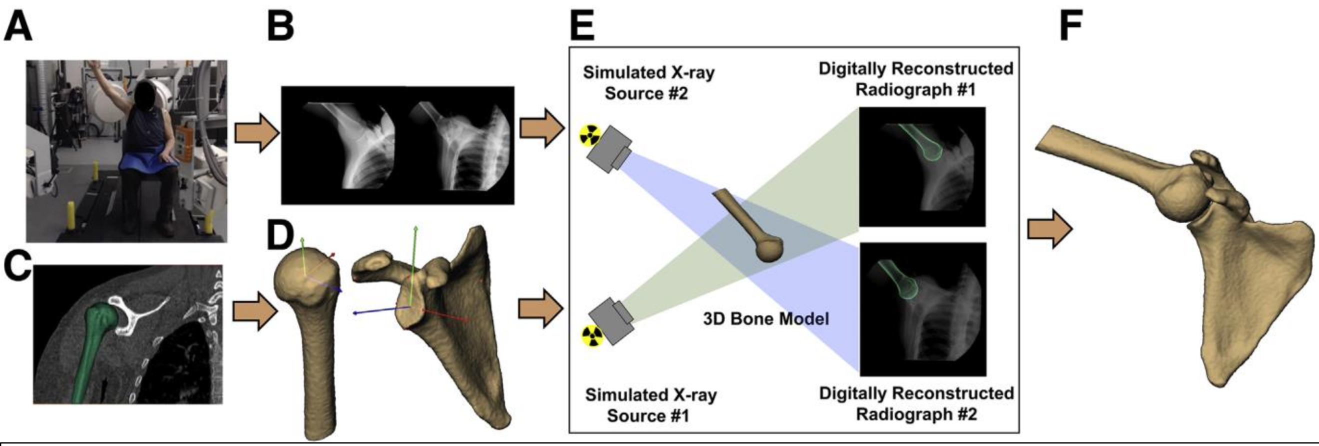

Figure 3. Workflow for creating Dynamic 3D bone images (from Kane et al. [16]): (A) Participants perform shoulder motion as instructed (B) synchronized biplane radiographs are collected. (C) Computed tomography scans of the affected shoulder are collected and (D) used to create 3D bone models with anatomical coordinate systems. (E) 3D glenohumeral positions are determined using a validated computed tomography model-based tracking process. (F) 6DoF kinematics are calculated.

Table 1. Outcome parameters of the dynamic biplanar radiographic image data analyses

Outcome parameter	*Description*
Kinematic data	*Position of scapula and humerus related to global body position, contact/minimum distance and surface distance map between scapula and humerus.*
Instability Quantification	*Relative horizontal, vertical, and mediolateral translations in mm from the neutral pose origin, subluxation, minimum distance between glenoid rim and humerus.*
Muscle Activation	*EMG potential of the of the infraspinatus, biceps brachii, anterior, middle, and posterior parts of the deltoid, clavicular part of the pectoralis major, latissimus dorsi, and upper trapezius muscles*

Muscle force computation

The AnyBody shoulder model, employed in previous research on the impact of rotator cuff tears (RCTs) and prosthetic shoulder implants [25][26][27] , integrates a kinematic model associating scapula, thorax and humerus, which constrains the inferior angle and medial boarder of the scapula to glide along an ellipsoid approximating the rib cage, whilst the scapulohumeral rhythm is defined as the ratio of glenohumeral elevation to scapulothoracic elevation [28] . Alternatively, the position of the bones can be defined from motion capture data, potentially inadequately representing the dynamic complexity inherent in instability scenarios. By driving patient-specific musculoskeletal models with precise kinematic data obtained through DBRI, we aim to comprehensively examine the glenohumeral biomechanics of anterior instability patients. Using our previously developed and validated segmentation network [29], the supraspinatus, infraspinatus, teres minor and subscapularis will be automatically segmented, and the deltoid, latissimus dorsi, and pectoralis major [24] will be manually segmented from all the MRI images by a clinical expert. The volume of each segmented muscle will be extracted. For each patient, musculoskeletal models from the pre- and post- therapy of the pathological and pre-therapy of the contralateral healthy shoulder will be generated from the segmented scapula and humerus from CT. The musculoskeletal models will be further scaled by the patient's height and weight and by the segmented muscle volumes of each shoulder. The models will be actuated by the humeral and scapular kinematics generated from DBRI imaging. The model outputs of glenohumeral joint force, force magnitude and moment arms of the aforementioned muscles and instability ratio, as well as the pre- and post- therapy muscle volumes and difference in muscle volume will be compared (Table 2).

Table 2. Outcome parameters of the biomechanical modelling

Outcome parameter	Description
Joint and Muscle Forces	*Glenohumeral joint reaction forces, forces of the shoulder muscles.*
Instability Quantification	*Instability ratio*
Muscle volume	*Pre and post therapy muscle volume, percentage change.*

Statistical Analysis

Differences in muscle volume, average maximum measured and calculated muscle forces, glenohumeral and scapulothoracic kinematics, instability ratio and clinical shoulder stability for the pre and post treated instable shoulder and the healthy contralateral shoulder will be analysed using paired t-tests. Additionally, to evaluate the effects of muscle volume, muscle activation and scapulothoracic kinematics on glenohumeral translations and instability ratio, single variable and multivariable regression analysis will be performed. The effect of these continuous variables on the clinical stability of the joint will be evaluated using logistic regression.

Timeline

The project will commence on 01.07.2024. Ethical approval will be sought prior to project commencement. In the first year of the project patients will be recruited (Milestone 1) and undergo MRI and DBRI studies by the end of Month 14 (milestone 2). Post therapy follow up studies are expected to be completed by the end of 2025 (18 Months) (Milestone 3). DBRI data analysis will be completed by the end of month 20 (Milestone 4) and statistical analysis and publication will be finalised by the end of Month 24 (Milestone 5).

Expected results

- Increased anteroinferior translation of the humeral head within the glenoid fossa and increased shoulder muscle activation in the affected shoulder during ABER compared to the healthy contralateral shoulder
- Reduced anteroinferior translation and improved apprehension test during ABER of the affected shoulder due to an increase in muscle volume after physical therapy
- Altered scapular kinematics and shoulder muscle activation in the affected shoulder compared to the healthy contralateral shoulder during ABER.
- Reduced differences in scapular kinematics of the affected shoulder compared to the healthy shoulder with increased muscle volume due to physical therapy

5. what contribution does the sitem-insel platform make to the project?

The preoperative and postoperative dynamic radiological investigations will be performed at the Dynamic Imaging Center (DIC) which is situated at sitem-insel. For this research project there will be close collaboration with Empa scientist and DIC's Co-Director Prof. Ameet Aiyangar.

Accurately and reliably assessing motion of the humeral head on the glenoid surface is a challenge. Static imaging techniques such as conventional X-rays, or even CT and MR imaging cannot quantify the motion path of the humeral head on the glenoid

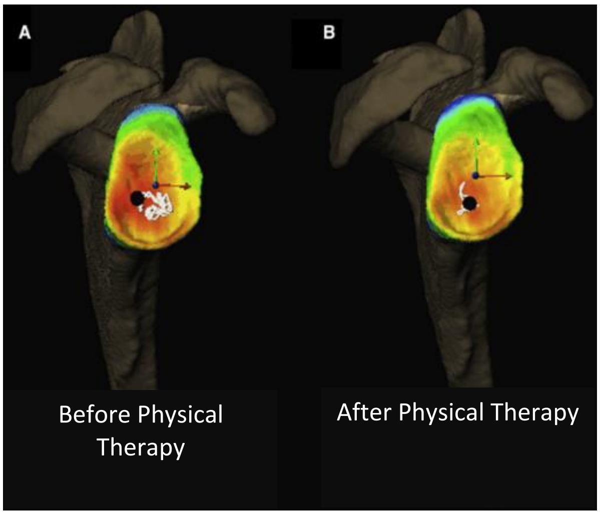

Fig. 4 Contact path of humeral head on glenoid surface during scaption movement shown by white line. (A) Larger contact path and divergence from mean joint center (black spot), reveals greater joint instability after symptomatic infraspinatus tear, (B) Reduced contact path and divergence from joint center reveals improved joint stability after physical therapy.[21]

during a functional shoulder movement. The Sitem-Insel platform will provide dynamic datasets with sub-millimeter accuracy based on acquisition of x-ray video-based imaging data during live motion. With this novel technique, bone motion can be directly captured without errors commonly associated with other dynamic data acquisition techniques such as surface marker-based motion capture methods. For this purpose, the DIC will be responsible for recording the dynamic images, and post-processing of the recorded raw, image-based datasets.
Based on these data, 3D segmental kinematics including rotation and translational components for the glenohumeral joint will be obtained. In particular, the translation data – i.e. the contact path of the humeral head on the glenoid surface, obtained from continuous motion, can reveal unique insights with respect to risk of subluxation or dislocation (e.g. Figure 4.) The DIC will also provide consultation on analysis and technical interpretation of the acquired datasets. The kinematic data will then be further analyzed and interpreted together with the team of Dr. M. Schär and Dr. K. Gerber to provide clinically relevant metrics for anterior shoulder instability.

6. Contribution to the University of Bern's Strategy 2030

Through the employment of state of the art medical imaging techniques, this proposed project supports strategic objective 2 of sub-strategy 4.2 of the University of Bern’s strategy for 2023 to “establish itself as a Swiss center for state of the art medicine”. By advancing the biomechanical knowledge of shoulder stability, the project will position the university of Bern as a leader in the field and thus contribute to the pursuit of “outstanding achievements across all medical research disciplines”. As an interdisciplinary project interfacing the fields of engineering and medicine, the proposed study will additionally contribute to sub-strategy 4.1 of the University to be a “Comprehensive University” that supports “high quality interdisciplinary and transdisciplinary research”.

7. literature

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