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# Simulator Based Experimental Motion Analysis of 3D Printed Artificial Shoulder Joint Geometries

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**Abstract**

The glenohumeral joint is an important joint with large mobility of the human upper extremity. In shoulder arthroplasty patients often has an unsatisfactory outcome. In order to understand the biomechanical complexity of the shoulder, a novel computer controlled experimental shoulder simulator with an innovative muscle control were constructed. The main component of the simulator includes the active pneumatic muscles to replicate the deltoid and the rotator-cuff function and two springs as passive muscle. The aim of this study is to evaluate the impact of a variation of shoulder joint geometries on shoulder biomechanics in the basis of motion analysis. The radius of the glenoid cavity varied from 28-33mm with 2.5mm increment while the radius the humeral head are varied from 20.1-25.1 with 2.5mm increment. The "teach-in" function of the simulator allows an operator to assign the movement to the simulator where the lengths of the pneumatic muscles are recorded. Then the simulator repeats the assigned movement according to the recorded muscles length. The daily living activities includes abduction/adduction, internal/external rotation with adducted arm, and circumduction. The results show promising repeatability of the simulator with minor deviation. However, damage on the surface of the humeral head has been found which should be further studied for both shoulder behavior investigation and the shoulder simulator optimization. Therefore, this study is a decent initial study toward the verification of the simulator and lead to a better understanding of shoulder biomechanical behavior to cope with the clinical problems in the future.

# 1 Introduction

The glenohumeral (GH) joint is the main important and high flexible joint for the motion of the upper extremity of the human body. The understanding of its complex movement is essential to cope with shoulder problems. In Germany, approximately 12,000 shoulder prosthesis are implanted each year (Loew 2010), and in the U.S., 67,000 up to 76,000 shoulder replacement procedures were performed in 2010 and 2011, respectively (Helmick 2014).

Many studies, for example (Deshmukh 2005) and (Gadea 2012) showed the shoulder prosthesis survivorship at 10 years was 93% and 88.13%, respectively. Therefore, it suggests that shoulder arthroplasty has proven a reliable treatment alternative. The problem coming along with shoulder arthroplasty is, that in one of ten patients the results is unsatisfactory (e.g. limited range of motion, loosening, and pain), even in the hands of expert surgeons (Cofield 2010). This shows the complexity of the shoulder, where the joint mobility and also its stability is mainly based on active muscle control with only a minor role for the glenohumeral capsule, labrum and ligaments (Veeger 2007).

Therefore, beside clinical studies, it is compulsory to be able to technically investigate the behavior of the shoulder biomechanics using shoulder testing apparatus. In our previous study (Verjans 2016), our shoulder simulator showed promising results of the repeatability of a human cadaver shoulder. We used an approach with adaptive muscle force generation and free motion. We tested shoulder abduction/ adduction, anteversion, and internal/ external rotation (Verjans 2016).

This paper presents the experimental set-up and first results of our study on the impact of a variation of shoulder joint geometries on shoulder biomechanics on the basis of a motion analysis in our novel computer controlled experimental shoulder simulator.

# 2 Materials and Methods

To vary the shoulder joint geometry, the experimental set-up (Figure 1) consisted of 3D printed joint geometries, which were fixed to a metal plate (scapular component). The 3D printed joints consisted of the humeral head and the glenoid component. We used an Ultimaker 2 (Ultimaker B.V., Netherlands) for printing the different shoulder joints. The radius of the glenoid cavity varied from 28-33mm with 2.5mm increment while the radius the humeral head are varied from 20.1-25.1 with 2.5mm increment, which covered majority European and Asian shoulder (Matsumura 2016, Iannotti 1992).

The scapular component was connected to the humerus component. The humerus component included an additional weight, which was attached to the distal end (imitating the forearm weight). Also optical markers for motion detection were connected rigid to the humerus.

We used a new developed shoulder simulator for testing (Verjans 2016). The shoulder simulator consisted of six active pneumatic muscles (DMSP, Festo, Esslingen, Germany) connected by Ultra-high-molecular-weight polyethylene (UHUMWPE) cables and pulleys, which replicates the main muscles in the shoulder joint. The six active pneumatic muscles represent each of the deltoid (anterior, lateral, and posterior part) and the rotator-cuff muscles (supraspinatus, infraspinatus + teres minor, subscapularis).

Moreover, springs and elastic bands act as passive muscles and connective tissue around the joint, respectively. Two springs represent pectoralis major muscle combined with latissimus dorsi muscle and biceps brachii muscle.

The sensory and measurement devices includes a muscular length measurement (WS10SG, ASM GmbH), a muscular force measurement (KM30z, ME measurement systems), a 6D force moment sensor (ATI), and an optical tracking system (Polaris Spectra, NDI). The data are being processed using a real-time data processing system (MicroAutoBox II, dSPACE).

When all the active and passive muscles are attached properly, a certain movement is manually given as an input for the simulator (teach-in process). The shoulder simulator could now repeat the teach-in motion. During the teach-in process, the active pneumatic muscles are force-controlled, where the length-changes in each active pneumatic muscle were recorded. After this process the simulator repeated the motion using the recorded changes of the muscles length. The experiments investigated the shoulder behavior for the following movement: abduction/ adduction, internal/ external rotation with adducted arm and circumduction.

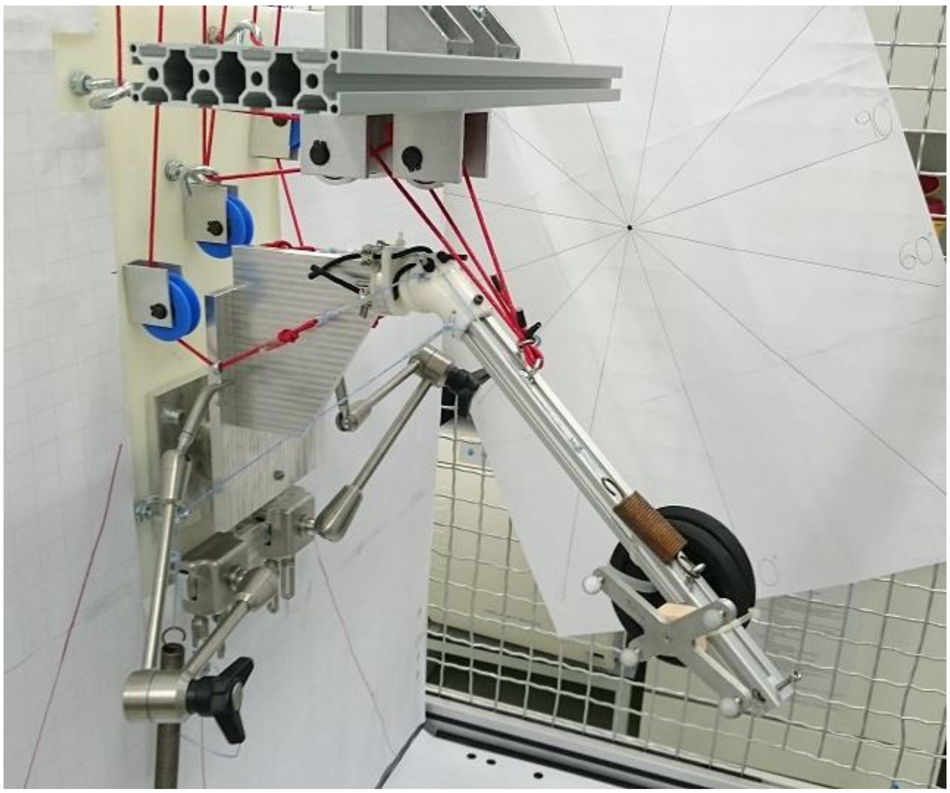

**Figure 1: The experimental setup**

# 3 Results

The results show a small difference of movement, when the dimension of the glenoid and humeral head varied. For example, in the circumduction case, shown in Figure 2, the shoulder kinematics in abduction angle, abduction plane angle, and internal rotation angle show a good repeatability, when varying the glenoid component. The trajectory plot shows minor deviation during flexion and abduction. However, during the extension phase, the height slightly drops as it moves toward the back and there is deviation during adduction. In addition, slightly damage on the surface of the humerus head has been found.

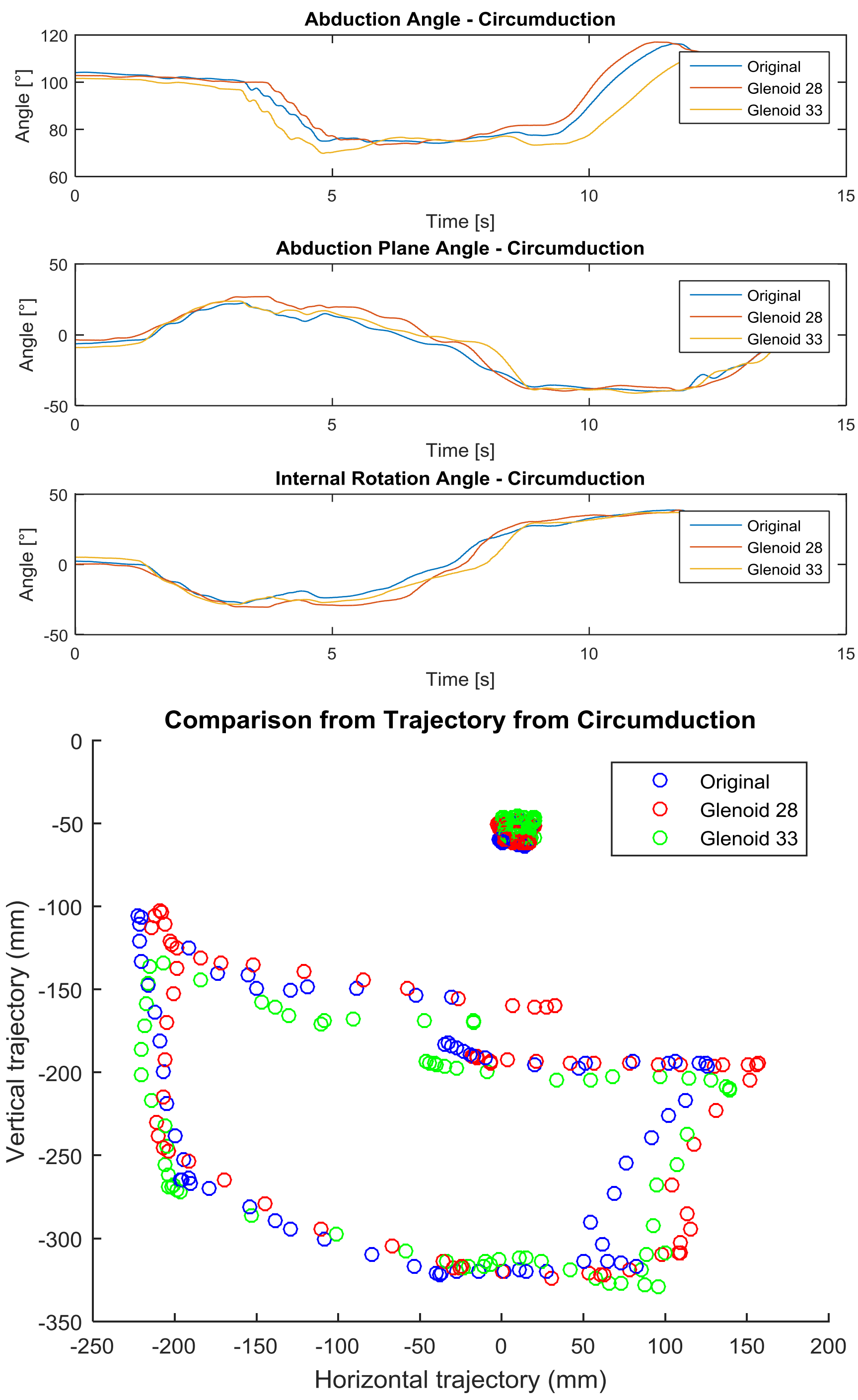


**Figure 2: The shoulder kinematics (above) shows the abduction angle, abduction plane angle, and internal rotation angle of the shoulder during circumduction and sagittal view of the trajectory of the humerus component at each end during circumduction (below)**

# 4 Discussion

We wanted to evaluate the influence on the shoulder biomechanics in case of the variation of the shoulder joint geometry. From the results, in general it shows that the shoulder simulator can successfully perform in both cases: force-controlled and the repeat process. The motions taught during the teach-in process were repeated for each movement according to the recorded muscle length with minor deviation even when the shoulder dimensions are varied. This could be implied that the joint mobility and stability is mainly based active muscle control with minor role for other passive factors like joint capsulae or ligament (Veeger 2007).

During our investigations, we found damages on the joint surfaces. The damage detected on the surface of the humeral head means, at a certain point the humeral head subjected to an unexpected stress concentration, for example dislocation. This could be presumably caused by a combination factors rather than a single factor such as the joint structure, joint constrain, and simulator function.

From the trajectory plot in Figure 2, the deviation during extension, adduction and at the end of abduction occurred when tension of one or more pneumatics muscle/s was released. Hence, not all the muscle force/s was acting on the shoulder model and caused inconsistency during the extension, adduction and at the end of abduction phase. This limitation refer to a literature, Verjans 2016, stated that the simulator still has limitations, where a better physiological behavior can be improved by, for example, optimizing the pneumatic muscle operation and length control function. Therefore, the simulator optimization and further investigation concerning the factors influence the shoulder function should be studied. Furthermore, the verification of the simulator is also a definite objective to assure the accuracy of the machine, which is essential in further shoulder biomechanical studies.

This paper introduces an initial process towards the shoulder biomechanical analysis that, hopefully, be able contribute to expand the understanding of the shoulder function to cope with the clinical shoulder problems in the foreseeable future.

# 5 Disclosures

The authors report no potential conflicts of interest.

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