

Experimental measurement of flexion-extension movement in normal and corpse prosthetic elbow joint

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Abstract

This paper presents a comparative experimental study of flexion-extension movement in healthy elbow and in the prosthetic elbow joint fixed on an original experimental bench. Measurements were carried out in order to validate the functional morphology and a new elbow prosthesis type ball head. The three-dimensional (3D) model and the physical prototype of our experimental bench used to test elbow endoprosthesis at flexion-extension and pronation-supination movements is presented. The measurements were carried out on a group of nine healthy subjects and on the prosthetic corpse elbow, the experimental data being obtained for flexion-extension movement cycles. Experimental data for the two different flexion-extension tests for the nine subjects and for the corpse prosthetic elbow were acquired using SimiMotion video system. Experimental data were processed statistically. The corresponding graphs were obtained for all subjects in the experimental group, and for corpse prosthetic elbow for both flexion-extension tests. The statistical analysis has proved that the flexion angles of healthy elbows were significantly close to the values measured at the prosthetic elbow fixed on the experimental bench. The studied elbow prosthesis manages to re-establish the mobility for the elbow joint as close to the normal one.

Keywords: elbow joint, prosthesis, elbow flexion-extension, experimental bench.

Introduction

The techniques used to measure the human kinematical parameters are modern tools that offer the possibility of measuring the joints kinematics and the biomechanical response to diseases of the musculoskeletal system. They are widely used within lower limb movement analysis and, in the last period, they are more and more applied to the upper limb. The human joint movement data are collected with different acquisition systems, are extracted, analyzed and are represented as temporal diagrams representing specific joint measures during the movement cycle. For the gait analysis over-ground or on the treadmill the used techniques are presented in [1–5]. A new version of the CaTraSys measurement system has been used to determine the trajectory of the human limb extremity during walking operation [6]. Experimental determination of joint mobility is presented with numerical and experimental results. The experimental methods used for data acquisition and kinematical analysis of the gait are also used in the case of the robotic structures [7]. Two types of methods which utilize markers can be distinguished: the local or segmental methods, which take into account the relative movements of the markers of a cluster attached to a body segment [8]; the methods which optimize relative segments orientation and position thanks to joint constraints [9, 10]. The authors propose to optimize joint centers and axis determination but no skin movement artifacts correction is performed during voluntary movements. Kinematics of the elbow joint is very important in orthopedic surgery. Many devices have been designed and optimized with this aim. Hand goniometers or video system acquisition were employed for measuring elbow kinematics [11]. Morrey *et al.* studied the motions of the elbow joint by measuring elbow flexion

and forearm rotation using an electronic goniometer [12]. Morrey & Chao used biplanar roentgenograms for calculating elbow joint motion, obtaining three-dimensional (3D) kinematics of the joint in their research [13]. Tanaka *et al.* used electromagnetic motion tracking data and described the first 3D elbow kinematic [14]. Lateral roentgenograms used a kinematic analysis of elbow kinematics by London [15]. In this research, London used a special Reuleaux technique, which was used for first time by Fisher to obtain the location of the axis of elbow flexion [16]. Bottlang *et al.* [17] used direct electromagnetic motion tracking to trace the passive and dynamic motion of the natural elbow joint.

Subjects, Materials and Methods

Experimental group of subjects

Nine male adult subjects participated in the experiment, with ages comprised between 26 and 45 years (an average of 29.9 years), without pre-existing pathology at the level of right elbow, the one on which the determinations were made. The subjects did not have pains, or any evidence or history of osteoarthritis, or any evidence of surgical interventions at the level of upper limbs. The experimental protocol was approved by the Ethics Committee of the Emergency County Hospital of Craiova, Romania. The subjects were informed about the experimental study and consented in writing.

The anthropometric data of the participants in the experimental tests of elbow joint are comprised in Table 1.

In Table 2, the main statistical indicators, which characterize the experimental group from the anthropometric point of view, are presented. It appears that the

values of standard deviations and coefficient of variability is well below the 15% value. The lowest values are recorded for arm segments that form the elbow joint. As a result, the experimental group is homogeneous and the results obtained for the values of statistical indicators are representative for the experimental group and for the experimental tests that are conducted.

Table 1 – Anthropometric data of the subjects who participated in the experimental tests

Subject	Age [years]	Weight [kg]	Height [cm]	Total length of arm (including palm) [cm]	Distance of shoulder joint–elbow joint [cm]	Distance of elbow joint–wrist joint [cm]
1.	30	83	172	77	31.5	27
2.	45	95	175	74	30	28
3.	26	92	173	73.5	33	27
4.	26	95	170	73	32	27
5.	30	92	190	94	37	31
6.	26	79	178	78	34	28
7.	32	75	175	73	31	26.5
8.	29	90	184	81	35	29
9.	26	69	170	74	32	26.5

Table 2 – Statistical indicators of the anthropometric data of the experimental group

Statistical indicators	Age [years]	Weight [kg]	Height [cm]	Total length of arm (including palm) [cm]	Distance of shoulder joint–elbow joint [cm]	Distance of elbow joint–wrist joint [cm]
Average	29.9	85	175.7	76.95	32.45	27.7
Standard deviation	4.30	9.09	6.65	6.61	2.39	1.40
Max.	40	95	190	94	37	31
Min.	26	69	170	72	29	26.5
Coefficient of variability [%]	14.63	10.70	3.79	8.59	7.35	5.05

Equipment

The experimental bench

To realize different biomechanical tests on a corpse prosthetic human elbow, first, we designed an experimental bench. The following criteria were taken into account: to allow flexion-extension and pronation-supination movements of elbow joint in different positions of upper limb; to allow the simulation of an actuation drawn upon human biological system. One of the most important advantages of the experimental bench consists in the possibility of testing other corpse or artificial joints and endoprostheses (knee, ankle, etc.), in their various positions. The second advantage consists in the experimental testing of different known endoprostheses, but, also, of new designed prototypes. In this study, a new elbow endoprosthesis prototype, type ball joint, designed by our team, is tested.

The virtual model of the experimental bench assembly is realized by our team using SolidWorks software [18, 19] and it is presented in Figure 1, where the components are: 1 – Base plate; 2 – Flange; 3 – Column; 4 – Maneuver wheels; 5 – Upper plate; 6 – Servomotor for the flexion-extension of forearm bones; 7 – Humerus; 8 – Elbow

endoprosthesis; 9 – Guiding pulleys for driving cables; 10 – Radius and ulna [20].

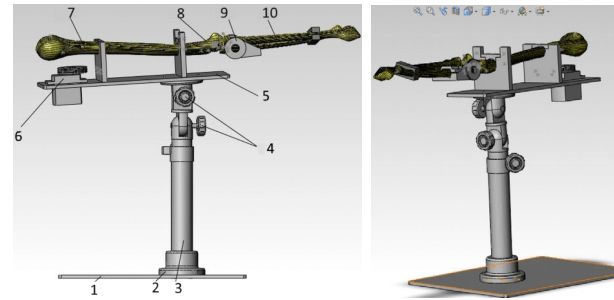


Figure 1 – Two views of the 3D virtual model of the experimental bench assembly.

The driving system is inspired from the study of bone and muscular system of human upper limb. Two electrical servomotors coupled with transmissions through cables and pulleys are used to actuate the experimental bench. The servomotor 6 is used for flexion-extension movements. Four steel cables glide through the flexible sheathings and are connected to a four-channel pulley. The second servomotor is used to rotate the radius around the ulna in the pronation-supination movement.

Based on the 3D virtual model assembly, the physical prototype of the experimental bench has been built of duralumin and stainless steel. The distance between base plate and upper plate could be modified and, thereby the structure of components 5–10 can glide after vertical axis. The structure of components 5 to 10 can be rotated in space by means of maneuver wheels 4. The elbow prosthesis was mounted on a skeleton of a human upper limb belonging to the same person. Radius and ulna were positioned anatomically and were secured together by a metal plate having the role of interosseous membrane. The olecranon ulna and humerus trochlea were cut with an oscillating saw. The two parts of the prosthesis were fixed with cement in the medullar canal of the ulna and, respectively, humerus. The newly formed assembly was mounted on the original experimental bench (Figure 2).

The repetitive flexion-extension and pronation-supination movements are initiated by a command and control system based on Arduino Duemilanove command board. In Figure 3, a few frames of flexion-extension movement of the prosthetic corpse elbow on the physical prototype of our experimental bench are presented.

The video based data acquisition system

In order to analyze the kinematics of human elbow flexion-extension movement, an optical motion analysis system was used, the SimiMotion data acquisition system based on Sony DCR-SR11 full HD video camera [2]. Designed for professional analyses of the plane and spatial movements, and presenting a high fidelity and accuracy in the field of sports, biomechanics, rehabilitation, industry, biology, the SIMI system has become an powerful tool for capturing and analyzing movement.

The analysis procedure is based on attaching the reflective markers on the biomechanical system points of interest, which have to be analyzed. By attaching the markers, the SIMI software automatically generates the equivalent model of the studied system, follows their motion on each frame captured by the video camera and

analyses simultaneously the positions of markers, in order to obtain the kinematical parameters of movement.

The block schema corresponding to SimiMotion data acquisition and processing system is given in Figure 4.



Figure 2 – A few positions that can be taken by upper limb bones in relation to base plate.



Figure 3 – Frames of flexion-extension movement of prosthetic elbow joint on the prototype of experimental bench.

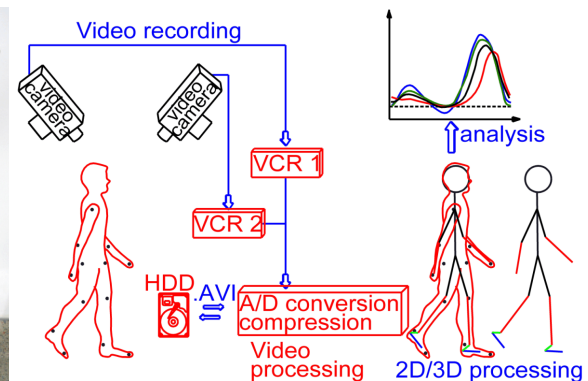


Figure 4 – Data acquisition block schema.

Description of experimental tests

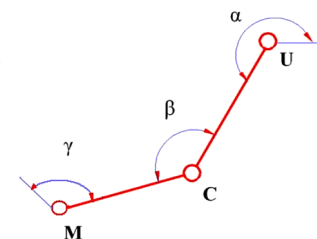
The experimental tests were carried out in the Laboratory of Biomechanics from the INCESA – Center of Advanced Research – of the University of Craiova. The steps of the protocol for each test were previously presented to each subject. The subjects accustomed with the tests by repeating them several times before starting the final experimental test. Two flexion-extension tests to evaluate a task – drinking from a cup – were carried out:

- Test 1: flexion-extension with a speed of one cycle/second;
- Test 2: flexion-extension with a speed of one cycle/two seconds.

The subjects were equipped with three passive markers attached to the right upper limb in the three predetermined points (Figure 5): 1 – Lateral edge of acromion–glenohumeral joint (shoulder); 2 – External epicondyle of humerus (elbow); 3 – Radial styloid–radiocarpal joint (hand).

The angles that characterize the movement of human upper limb from the cinematic point of view: α – angle formed by the arm with horizontal line, β – angle between arm and forearm, γ – angle between forearm and hand).

Figure 5 – The anatomical joint of human arm.
U – Shoulder joint;
C – Elbow joint;
M – Hand joint.



Results

All these points were captured during the tests by Sony video camera and their trajectories were redesigned automatically by SimiMotion program. The diagram of flexion-extension angles of right elbow joint of subject 4 is presented in Figure 6. In Figure 7, the variation in time of the angular flexion-extension velocity of human elbow joint for subject 4 is presented.

The corresponding graphs were obtained for all the subjects in the experimental group, for both flexion-extension tests. In Figure 8, the variation in time of flexion-extension angle [degrees] of prosthetic corpse elbow joint on the experimental bench for Test 1 is presented.

It can be seen that the flexion-extension movement performed on the bench is a cyclic movement, unlike

human flexion-extension movement, which is a movement that shows a degree of variability from one individual to another and from one cycle to another for the same subject.

Statistical analysis of experimental data

The angular amplitudes of human elbow flexion-extension have been obtained for each subject from the report generated by the gathering system, as data files type *.txt*. All data files have been processed in Excel and MATLAB and then they were assessed. For more specific results, considering the natural biological variability of healthy elbow mobility from one individual to another, six consecutive cycles were selected for each subject and for each test on the artificial bench and these cycles were normalized by interpolation with Cubic splines functions, by means of MATLAB mathematical virtual environment [21]. The cycles were reported on the abscissa, at a scaling from 0 to 100%. The average angle was determined as being the arithmetic mean of the data that correspond to movement cycles.

In Table 3, the values of main statistical indicators calculated for each one of the six normalized cycles and also for the medium cycle, corresponding to Test 1 of subject 4 are presented.

Table 3 – Main indicators for the six normalized cycles and for the medium cycle: Test 1 of subject 4

Statistical indicators	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6	Medium cycle
Max.	136.34	138.26	137.68	138.12	139.12	136.68	137.51
Min.	4.86	4.23	5.20	4.35	8.16	6.25	7.46
Amplitude	132.48	134.03	132.48	133.77	130.96	130.43	131.05
Average	84.31	77.68	79.27	70.91	76.81	84.82	78.84

The report of normalized cycles is made to an abscissa of 100%. The curves of flexion-extension angles corresponding to each cycle and to medium cycle for subject 4 were drawn and they are shown in Figure 9.

The curves of flexion-extension angles corresponding to medium flexion-extension cycle of each subject and to final medium cycle of entire experimental group are drawn in Figure 10.

In a similar manner, the graphs of normalized cycles and average cycles were determined for the second test, that corresponding to the frequency of one cycle in two seconds.

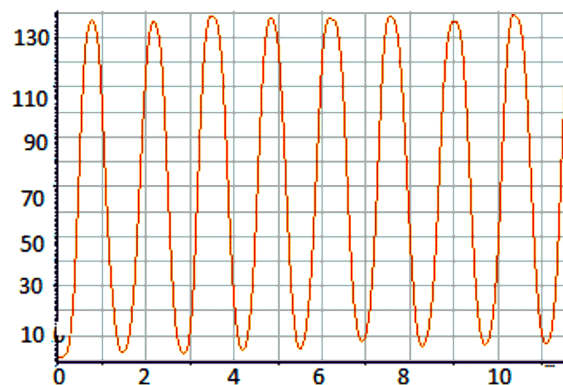


Figure 6 – Variation in time of flexion-extension angle [degrees] of human elbow joint for subject 4.

The main statistical indicators of average cycles of each subject in the experimental group, as well as of the medium flexion-extension cycle at the level of the entire experimental group are presented in Table 4, for Test 1, and in Table 5 for Test 2.

Table 4 – Main indicators for the nine subjects: Test 1

Statistical indicators / Subject No.	Max.	Min.	Amplitude	Average
1.	150.07	6.37	143.70	79.95
2.	139.58	23.47	116.11	79.39
3.	137.51	21.46	116.05	80.61
4.	143.90	16.99	126.92	81.36
5.	141.47	26.92	114.55	83.98
6.	146.08	17.59	128.49	79.03
7.	140.17	0.13	140.04	66.61
8.	136.38	11.12	125.26	75.40
9.	143.88	1.55	142.33	68.74
Medium cycle	140.27	14.23	126.04	77.23

Table 5 – Main indicators for the nine subjects: Test 2

Statistical indicators / Subject No.	Max.	Min.	Amplitude	Average
1.	152.73	17.91	134.82	86.16
2.	144.15	20.25	123.90	78.59
3.	129.02	15.64	113.38	72.11
4.	137.51	7.46	130.05	87.33
5.	135.41	23.82	111.59	81.12
6.	146.71	17.65	129.06	79.60
7.	141.76	1.64	140.12	66.72
8.	133.21	7.75	125.46	68.25
9.	144.26	4.23	140.03	69.45
Medium cycle	139.96	13.73	126.23	76.59

In Figure 11, the normalized cycles of flexion-extension angle [degrees] of the prosthetic corpse elbow joint mounted on the experimental bench are presented.

The main statistical indicators for six consecutive cycles of prosthetic corpse elbow are presented in Table 6. The maximum flexion-extension angle values varies for the six consecutive cycles from 133.94° to 135.82°, with an average value equal to 134.84°, very close of 134.68°, which is the maximum value of the medium cycle (standard deviation is 0.567°).

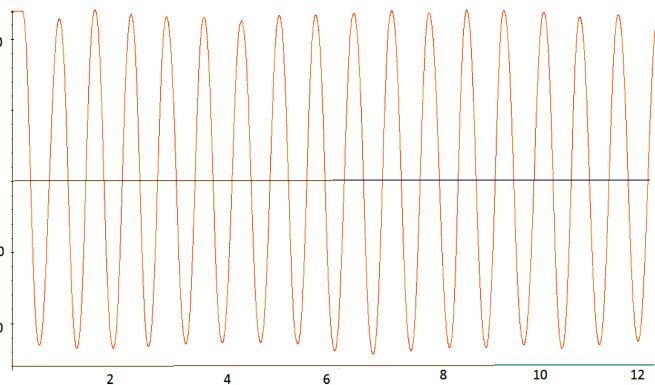


Figure 7 – Variation in time of flexion-extension angular speed [degrees/second] of human elbow joint for subject 4.

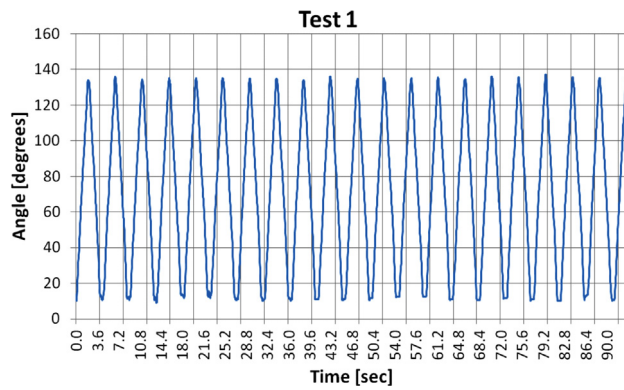


Figure 8 – Variation in time of flexion-extension angle [degrees] of prosthetic elbow joint on the experimental bench for Test 1.

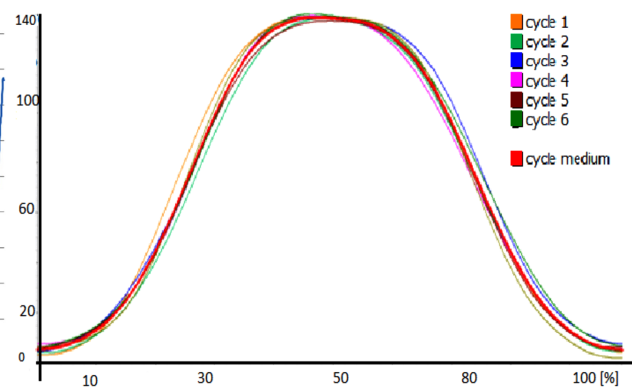


Figure 9 – Normalized diagrams of flexion-extension angles corresponding to each cycle and to the average cycle for subject 4.

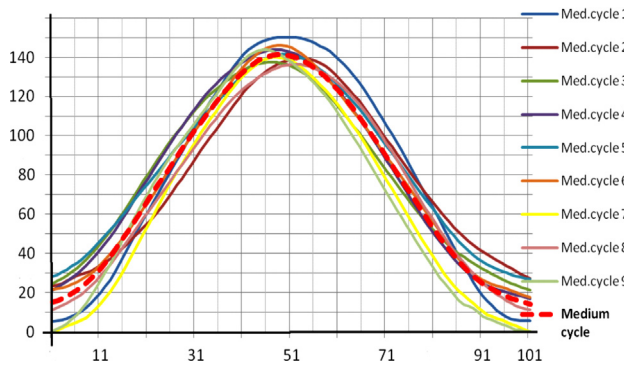


Figure 10 – Normalized diagrams of flexion-extension angles corresponding to average cycles of each subject and to the final average cycle for test 1.

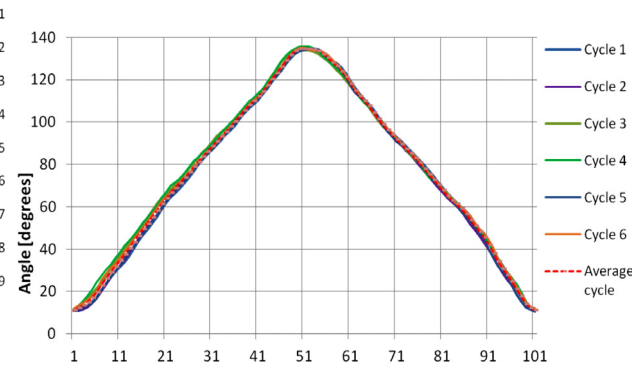


Figure 11 – Normalized flexion-extension cycles corresponding to the prosthetic corpse elbow mounted on the experimental bench.

Table 6 – Main statistical indicators for six consecutive cycles of prosthetic corpse elbow

Statistical indicators / Cycle No.	Max.	Amplitude	Average
1.	134.81	123.95	75.52
2.	134.67	123.81	74.91
3.	133.94	123.85	76.80
4.	135.82	124.26	77.26
5.	134.69	124.11	75.02
6.	135.44	123.74	76.98
Average cycle	134.89	123.95	76.22

Discussion

Analyzing the acquired and processed data for the elbow flexion-extension movements of the nine subjects, we can conclude that they are comprised in the normal movement interval according to standard data and to other papers.

By comparing the amplitudes of the six flexion-extension cycles of human elbow joint of subject 4, it can be seen that the values varied between 130.43° and 134.03° and their medium value is of 132.37°, with a standard deviation of 2.35°, in relation to the maximum value of the medium cycle amplitude, which is equal to 131.05°. These minor differences prove a good repeatability of the performance of flexion-extension movement exercises imposed for subject 4. All subjects performed the tests with a good repeatability, the differences being very small, within the admissible limits. The same obser-

vations can also be made for the other subjects in the experimental group.

By comparing the range of elbow flexion of the nine medium cycles of human elbow joint corresponding to the nine subjects in the experimental group for Test 1 (Table 4), it can be seen that the values varied between 114.55° and 143.70° and their average value is 127.60°, with a standard deviation of 4.251°, in relation to the range value of the medium cycle, which is equal to 126.04°. The two range values are very close, without significant differences.

Similarly, in the case of Test 2 (Table 5), it can be seen that the range values varied between 114.55° and 143.7° and their average value is equal to 128.11°, with a standard deviation of 4.33°, in relation to the range value of the medium cycle, which is equal to 126.04°, so the two maximum values are very close. These minor differences prove a good repeatability of the performance of flexion-extension movement exercises imposed for the entire experimental group for both tests.

Cooper *et al.* [22] studied functional upper limb motion and found ranges of motion of 105–125° elbow flexion, which is comparable to the 126° elbow flexion as found in this study. Magermans *et al.* [23] used electromagnetic 3D tracking to evaluate six functional tasks: combing their hair, perineal care, eating with a spoon, reaching, washing the axilla, and lifting a bag. Flexion values ranged from 61° to 135.7°, for eating with spoon task the value of amplitude value for elbow flexion being comprised in the range 117–131.5°, with a standard deviation equal to 7.5°. Using an electrogoniometer,

Chao *et al.* reported a range of 82–123° for elbow flexion in a group of 18 female subjects in eating [24]. Morrey *et al.* [12] found 107° elbow flexion for a combing hair position. Examining three feeding activities, Safaee-Rad *et al.* [25] found that drinking from a cup, eating with a fork, and eating with a spoon all required a range of flexion from 70° to 130°, the range for drinking from a cup was about 125°, which is similar with the range value obtained in this study.

Raiss *et al.* used an optical tracking system to evaluate 10 activities of daily living and they found a range of motion equal to 110° (from 36° to 146°) [26]. Three functional tasks – eating a meal, shampooing one's hair, and washing one's face – were evaluated [27]. Flexion values ranged from a mean of 140° for washing one's face to 151° for shampooing one's hair.

Positional range of motion results was presented by Sardelli *et al.* [28]. The minimum flexion (mean and standard deviation) required was 27°, which was found with reaching to tie a shoe. For eating a meal, the range of flexion is about 126°, very close of our results.

The values of flexion extension angle for the cyclic movement of prosthetic corpse joint mounted on the experimental bench are comprised in the interval (8.25°; 135.82°) for Test 1 and (7.74°; 137.76°), respectively, for Test 2. It can be seen that the amplitudes of the movement in the case of human elbow and respectively, of prosthetic corpse elbow are close in size, with a difference of 1.5% (for Test 1) and 1.85%, respectively, (for Test 2), which means that the elbow prosthesis proposed manages to re-establish a mobility for elbow joint as close to the normal one of a healthy joint.

The maximum values of the medium elbow cycles for the nine subjects and for the six cycles of prosthetic corpse determined during the performed trials were compared and tested with an unpaired Student's *t*-test, considering $\alpha=0.05$. The *p*-values corresponding to these tests are calculated using ANOVA. The maximum flexion angles were not significantly different ($t_{\text{calc}}=2.027 < t_{\text{cr}}=2.14$ and $p=0.077 > 0.05$). In a similar manner, the average values for the nine subjects and for the six cycles of corpse elbow were compared and the values were not significantly different ($t_{\text{calc}}=2.01 < t_{\text{cr}}=2.14$ and $p=0.822 > 0.05$).

☐ Conclusions

The study presents a comparison of the elbow flexion-extension movement based on the experimental data gathered for healthy subjects and for the prosthetic corpse elbow mounted on the experimental bench. The 3D model and the physical prototype of our experimental bench used to test elbow endoprosthesis at flexion-extension and pronation-supination movements are presented. Experimental data for two different flexion-extension tests for the nine subjects and for the prosthetic corpse elbow were acquired using SimiMotion video system. The statistical analysis has proved that the flexion angles of healthy elbows were significantly close to the values measured at the prosthetic elbow fixed on the experimental bench. Also, the range of motion obtained in this study for flexion elbow is similar with the values obtained by other authors.

We can conclude also that the studied elbow prosthesis manages to re-establish the mobility for the elbow joint as close to the normal one. The final conclusion is that the proposed experimental bench designed and carried out allows to test the prosthetic corpse elbow and it also presents the advantage that it can be used for experimental testing of different endoprosthesis joints (knee, ankle, joints, etc.), in their various positions.

Conflict of interests

The authors declare that they have no conflict of interests.

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