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Elbow joint model with active muscle force †

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Abstract

Voluntary and reflexive muscle activation of the human elbow joint is investigated by both subject tests and numerical simulations. A jerk loading is applied to extend the elbow joint with different muscle tensing and pre-recognition conditions. Inter- and Intra-subject variations of the hand displacement are analyzed for an objective assessment of the active response at the elbow joint to the external perturbation. A finite element elbow model is developed using passive kinematic joint elements and active torques which have PID (Proportional–integral–derivative) close loop control. The simulation result from this FE model is compared with test results and shows a good correlation.

Keywords: Digital human body model; Inter- and Intra-subject variations; Jerk loading; Voluntary and reflexive muscle activation

1. Introduction

Digital human body models (DHBM) have been widely adopted in various CAE processes of vehicle design, e.g., car crash simulation for the prediction of injury risk and riding comfort simulation for the assessment of occupant discomfort. For most of such cases, the DHBM is in 3D finite element mesh shape so that it can mechanically interact with vehicle structures such as seat, safety belt and airbag. Thanks to efforts from many researchers, there is a significant advancement in human body modeling (www.ghbmc.com), e.g., mechanical behavior of biological tissue, but the active human response with voluntary and reflexive muscle activation that affects occupant kinematics are still remaining as a great challenge.

Muscle tensing of bracing occupants produces larger axial forces, stress redistribution within bones, increase in effective mass and stiffness, altered kinematics, and less excursion and smaller joint rotations [1]. Voluntary and reflexive muscle activation of a vehicle occupant is modeled by active joint elements at each anatomical joint position (e.g., shoulder, knee, spine and etc.). There are two basic elements at each joint, i.e., passive kinematic joint elements and torque actuators.

Assuming that a co-contraction of the agonist and antagonist muscles stiffens the joint articulation, the spring constant and damping coefficient of the passive kinematic joint elements are adjusted for the different levels of co-contraction, which is considered as a major mechanism of voluntary muscle activation. A so-called vestibular reflexive muscle activation [2, 3] for the posture stabilization is modeled by active torques with PID (Proportional–integral–derivative) close loop control. Active torque, the control signal, is a sum of proportional, integral, and derivative terms between current and reference states of the joint angle.

Tests of jerk loading applied to elbow joints, which are relatively simple one dimensional articulations, are performed with live human subjects to identify and quantify the active response with different muscle conditions. Two kinds of numerical elbow models, i.e., 3D finite element mesh and Modelica models, are built to reproduce the active response to the jerk loading and further to elucidate the kinesiologic behavior of the bracing human joint.

2. Jerk loading to elbow joint extension

During the vehicle driving or just riding, external loadings are often applied to the occupant as perturbations, e.g., vertical bumping on rough road, lateral G force at cornering, and autonomous braking with ADAS (Advanced driver assistant system). It would be quite natural that the occupant spontaneously braces to keep his (or her) upright sitting posture. In order to mimic this kind of perturbation from the vehicle in motion and the bracing behavior of the occupant, jerk loadings to the elbow joint extension are performed as follows.

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Table 1. Age and anthropometric of data of test subjects.

Subject #	Age (years old)	Height (cm)	Weight (kg)	Fat free mass (kg)*	Forearm weight (kg)**
1	28	172	81.8	56.4	1.898
2	29	170	68.1	53.6	1.618
3	24	179	73.7	52.5	1.734
4	28	165	67.5	50.9	1.605
5	31	174	72.9	56.1	1.717
Avg. (S.D.)	28 (2.3)	172 (4.6)	72.8 (5.1)	53.9 (2.1)	1.714 (0.11)

*: From inbody analysis
**: Calculated from GEBOD [4]

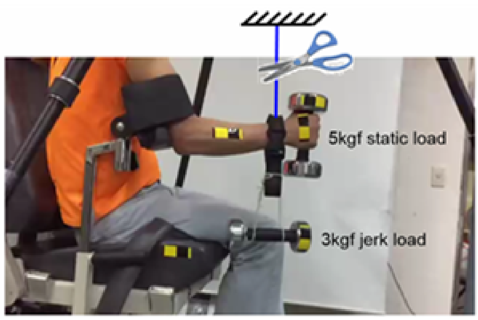


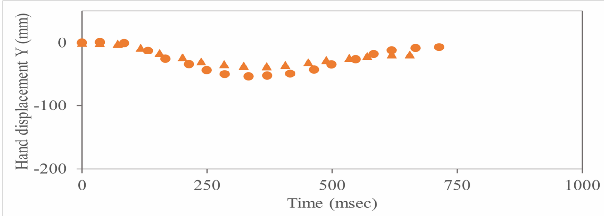
Fig. 1. Test setup for jerk loading at the elbow joint.

2.1 Anthropometry of test subjects

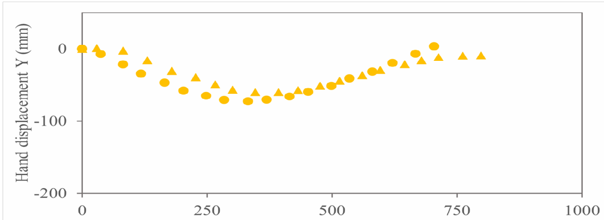
Five male subjects are recruited and their individual and average age and anthropometric data are listed in Table 1.

2.2 Jerk loading test

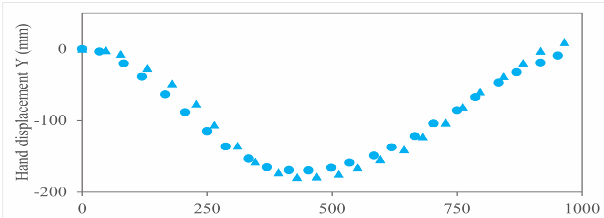
The elbow joint with simple 1-DOF is selected. The upper body and upper arm of the test subject are restrained and the elbow joint angle is to maintain its initial position, i.e., keeping the forearm levelled before and after the jerk loading. There are two kinds of loadings, a 5 kgf static loading on the hand and a 3 kgf jerk loading on the wrist which is initially carried by a string and just becomes a jerk load when the string is cut (See Fig. 1). The subject is exposed to two test conditions, 1) co-contraction versus single contraction and 2) recognition versus unrecognition of jerk loading. Co-contraction or single contraction is respectively attempted by contracting both the agonist (e.g., biceps) and the antagonist (e.g., triceps) muscles, or only the agonist muscles. Recognition of the jerk loading by the test subject is made by letting him to make his own observation of the action of the string cut, i.e., open eye condition. On the contrary, the closed eye condition does not allow the test subject to become aware of the precise moment of the string cut. There are thus a total of four cases of test conditions, "open eye tensed" (recognized with co-contraction), "closed eye tensed" (unrecognized with co-contraction), "open eye relaxed" (recognized with single contraction), and "closed eye relaxed" (unrecognized with single



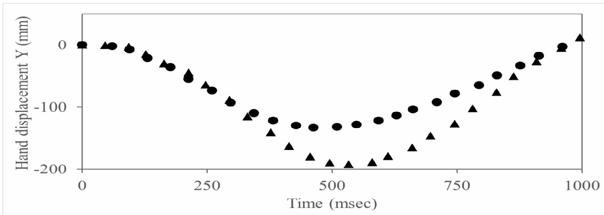
(a) Open eye tensed



(b) Closed eye tensed



(c) Open eye relaxed



(d) Closed eye relaxed

Fig. 2. Intra-subject variation: Typical hand displacements in vertical direction (y) due to the jerk loading from subject #2 (●: 1st try, ▲: 2nd try). Results of four other subjects are presented in the Appendix.

contraction). All five test subjects have two trials for each case of four test conditions.

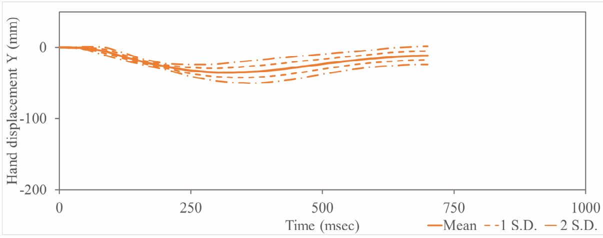
2.3 Measurement of hand motion

Typical hand displacement patterns, digitized from video, are shown in Fig. 2. Intra-subject variations are quantitatively assessed by CORA (CORrelation and Analysis, http://www.pdb-org.com/de/information/18-cora-download.html) score as listed in Table 2. All five test subjects showed high CORA scores with "open eye relaxed" conditions, i.e., good repeatability between two trials at the recognized with single contraction muscle condition. It is speculated that the cases with low CORA score are due to the poor coordination of the muscle tensing condition of the subject, e.g., the closed eye relaxed case with test subject #1.

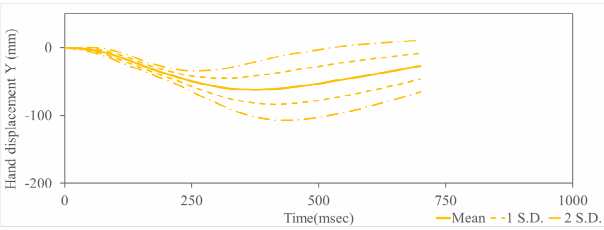
The inter-subject variation is also represented by test corri-

Table 2. CORA score for Intra-subject variations.

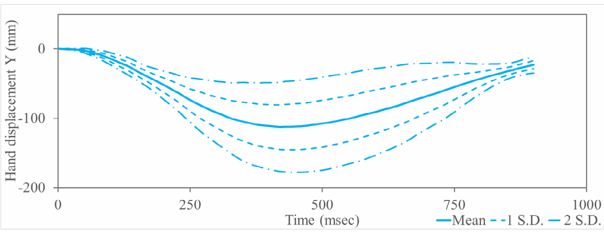
Subject #	Open eye tensed	Closed eye tensed	Open eye relaxed	Closed eye relaxed
1	0.699	0.967	0.957	0.493
2	0.746	0.732	0.948	0.768
3	0.962	0.642	0.955	0.898
4	0.365	0.828	0.720	0.851
5	0.546	0.766	0.795	0.914
Mean (S.D.)	0.693 (0.21)	0.787 (0.11)	0.875 (0.10)	0.785 (0.15)



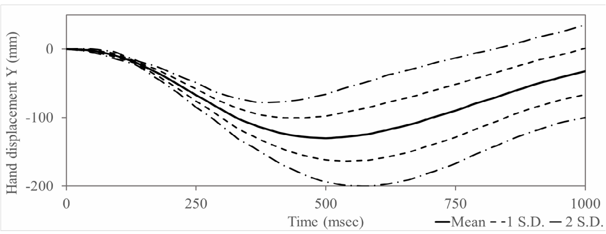
(a) Open eye tensed



(b) Closed eye tensed



(c) Open eye relaxed



(d) Closed eye relaxed

Fig. 3. Inter-subject variation: Test corridors and mean hand displacements of five test subjects (1 S.D.: Inner corridors with mean ± standard deviation, 2 S.D.: Outer corridors with mean ± 2 x standard deviation).

dors with mean hand displacements as shown in Fig. 3. The open eye tensed condition shows the least width between upper and lower corridors while the open eye relaxed condition has largest.

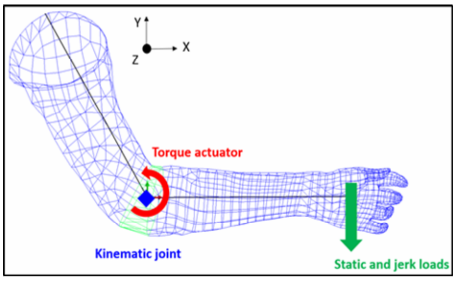


Fig. 4. A finite element elbow model of the active elbow joint.

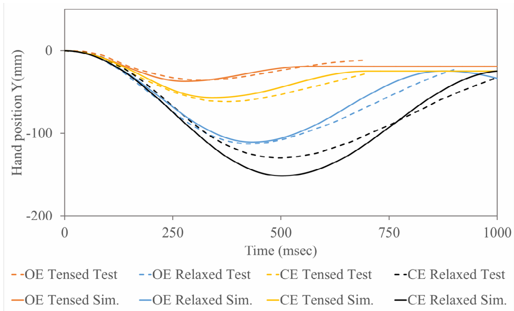


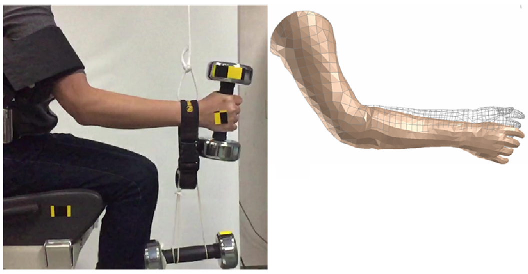
Fig. 5. Comparison of hand displacements between subject test and simulation.

3. Finite element active elbow model

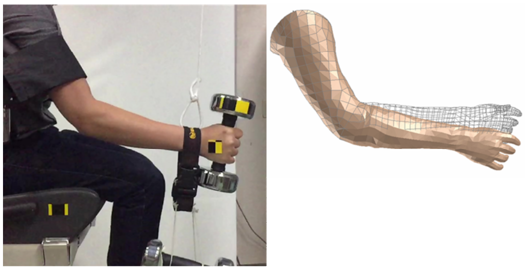
A finite element elbow joint model is shown in Fig. 4. Two rigid bodies, i.e., the upper and lower arms are articulated by a one dimensional kinematic joint element that represents the elbow joint. The dynamic properties of the two rigid bodies are assigned from the average data of the five test subjects.

3.1 Modeling of the active elbow joint

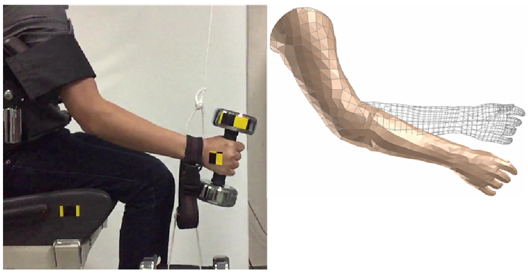
The numerical modeling of the elbow joint and its active response to the jerk loading is designed by implementing two mechanical components, a passive 1D kinematic joint element and a torque actuator. The linear stiffness and damping coefficient of the passive 1D kinematic joint element present the level of co-contraction that stiffens the elbow joint articulation. Voluntary and reflexive muscle activation responding to the jerk loading is modeled by the torque actuator with a PID close loop feedback control. Considering that the test subject tries to keep the initial elbow joint angle, torque (Mz) is activated to minimize the error which is the difference between the initial and current elbow joint angles. Meijer et al. [5] and Brolin et al. [6] presented successful applications of the active torque with PID control to their active human body models. Gain values for the PID control, i.e., Proportion, Integral, and Derivative terms determine the rates of torque generation. Faster torque generation with larger gain values stands for the recognition of jerk loading, i.e., "open eye" condition in the subject test. On the other hand, "closed eye" condition stands for unrecognized and thus more reflexive response that is modeled by smaller gain values. The comparison of hand displacements between subject test and simulation for four cases is shown in Fig. 5. The



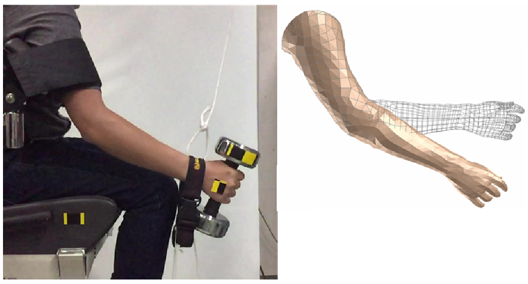
(a) Open eye tensed



(b) Closed eye tensed



(c) Open eye relaxed



(d) Closed Eye Relaxed

Fig. 6. Comparison of hand position at the maximum elbow extension between subject test (1st trial of Subject #4) and simulation.

comparison of hand position at the maximum elbow extension between subject test and simulation is shown in Fig. 6.

3.2 Hypothesis on the modeling of active elbow response

Table 3 lists modeling parameters of the active elbow joint for all four cases. The derivative term in the PID close loop control turns out to be insensitive in this simulation of active response to the jerk loading and is thus excluded. Those parameters were estimated by a heuristic method (trial and error) and based on the following hypotheses;

(1) The muscle condition e.g., co-contraction (tensed condition) vs. single contraction (relaxed condition) is modeled by the damping coefficient of the K-joint as shown in Fig. 7.

Table 3. Modeling parameters and CORA score of the active elbow joint model.

Modeling parameters	Open eye tensed	Closed eye tensed	Open eye relaxed	Closed eye relaxed
Damping C. (kNms/rad)	-1.5/1.5	-1.5/1.5	-1.5/0.5	-1.5/0.5
Stiffness (kNm/rad)	0.1	0.1	0.1	0.1
K_p (kNm/rad)	80	50	80*0.35	50*0.35
K_i (kNms/rad)	0.015	0.015	0.015*0.35	0.015*0.35
PID control latency(ms)	0	30	0	30
CORA score*	**0.916**	**0.897**	**0.950**	**0.892**

* Calculated between test and simulation in Fig. 5

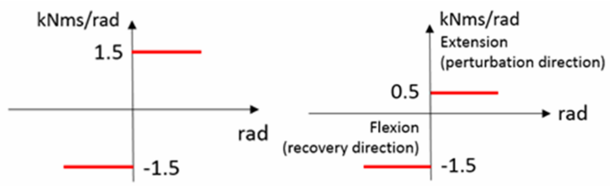


Fig. 7. Damping coefficients for different muscle tensing conditions (left: Tensed, right: Relaxed).

(2) The stiffness of the K-joint is dependent on inter-subject variations, e.g., muscular structure, gender, etc.

- Muscular build (stronger) arm ↑, male > female, and so on.

(3) Recognition of perturbation (Open eye vs. closed eye) is controlled by gains of PID close loop control.

- Relaxed condition (single contraction) has decreased gains by a factor of 0.35 than tensed condition (co-contraction).

(4) Muscle reflex latency (delay), 30 ms is given to the closed eye condition.

The correlation between test and simulation results for all four cases are qualitatively analyzed by the CORA score as in Table 3. Open eye condition, i.e., recognition of jerk loading, shows better correlation slightly for both tensed and relaxed muscle conditions than closed eye condition (0.916, 0.950 > 0.897, 0.892).

4. Whole body modeling

The same modeling scheme of active response at the elbow joint is extensively applied to the whole body model. The version of the multi-body model (c.f., deformable body model) consists of 15 rigid body segments and 14 articulated joints (Fig. 8). Each articulated joint has either 1 DOF (e.g., elbow, knee, etc.) or 3 DOF (e.g., shoulder, hip, spine, etc.) depending on its biomechanical characteristics. The same kind of passive kinematic joint element and active torque as in the active elbow joint model are implemented but their mechani-

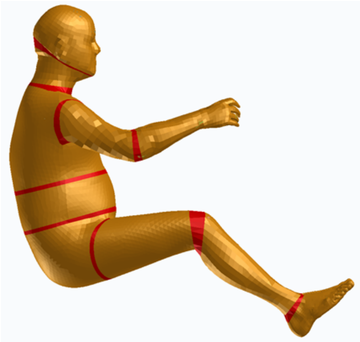


Fig. 8. Whole body model with 15 rigid body segments and 14 articulated joints.

cal characteristics, e.g., the moment-angle curve and damping coefficient, are dissimilar to each other. The errors to be removed by active torques at articulated joints are a composite function of joint angle changes at every body segment. A human driver voluntarily and/or reflexively braces to maintain its upright sitting posture against various kinds of G-forces during vehicle maneuvering, such as emergency braking, lane change, cornering, etc. Validation of the active human body model against the test data from open literature [7] is now in progress.

5. Discussion

The SISO (Single-input single output) problem with 1D active elbow joint model becomes a MIMO (Multiple-input multiple output) problem with the whole body model. Human driver's muscle recruitment strategy of active response to brace against external perturbations belong to the quite complicated behavioral kinesiology. Also inter- and intra-subject variations make the active human body model an exciting challenge.

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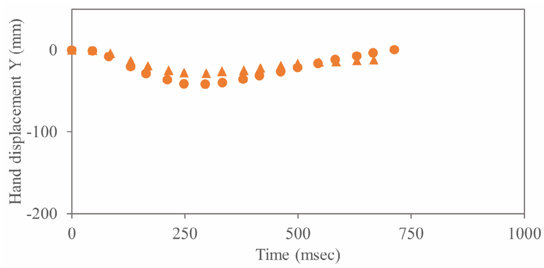
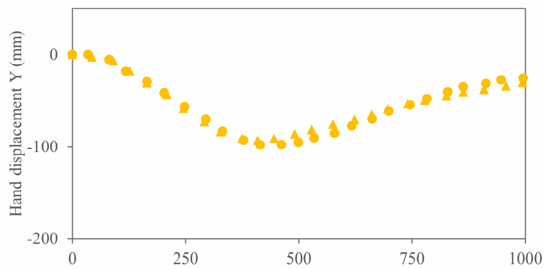
Appendix

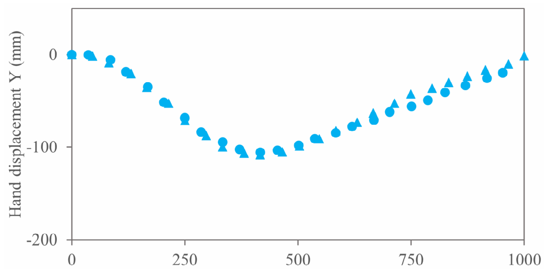
Hand displacements in vertical direction (y) due to the jerk loading (supplementary data for Fig. 2 with Subject #2).



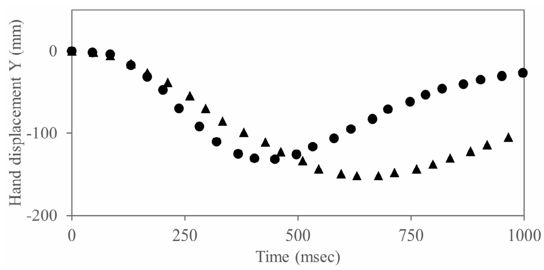
(a) Open eye tensed



(b) Close eye tensed

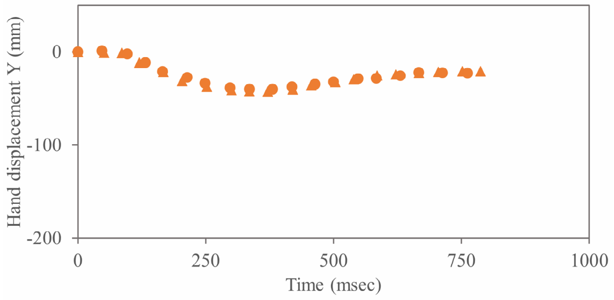


(c) Open eye relaxed

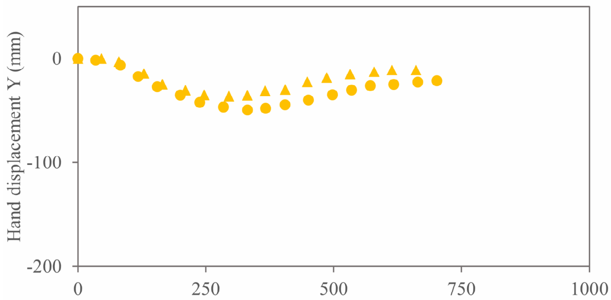


(d) Close eye relaxed

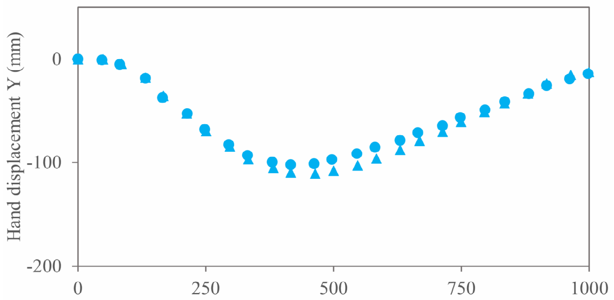
Fig. A.1. Subject #1 (●: 1st try, ▲: 2nd try).



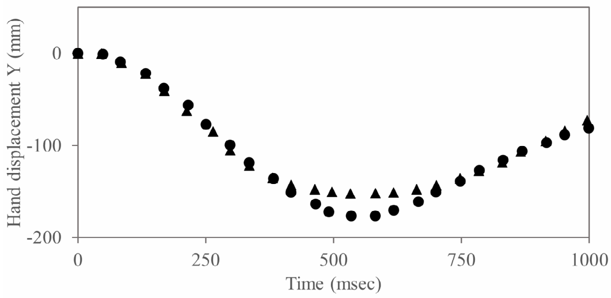
(a) Open eye tensed



(b) Close eye tensed

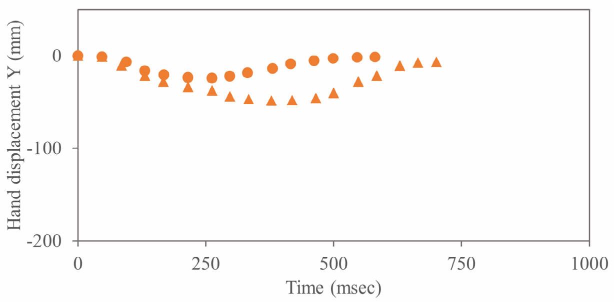


(c) Open eye relaxed

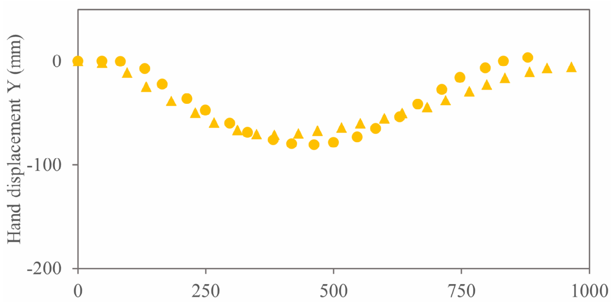


(d) Close eye relaxed

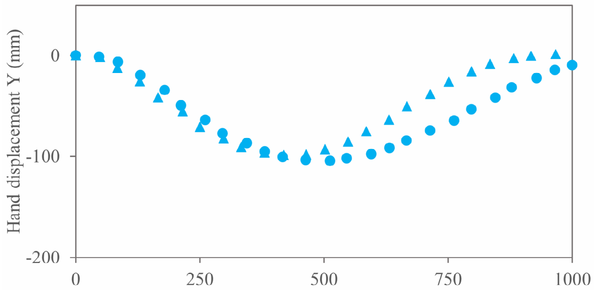
Fig. A.2. Subject #3 (●: 1st try, ▲: 2nd try).



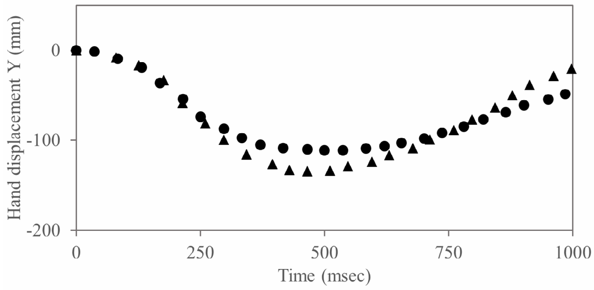
(a) Open eye tensed



(b) Close eye tensed

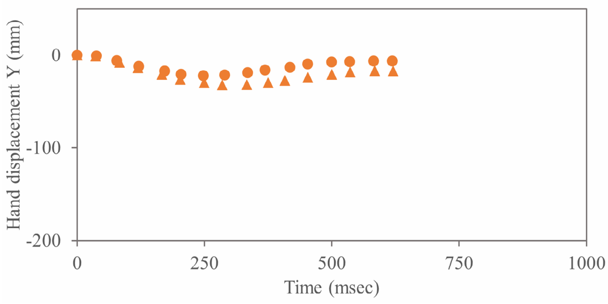


(c) Open eye relaxed

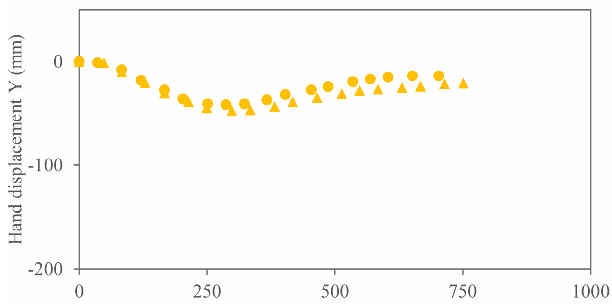


(d) Close eye relaxed

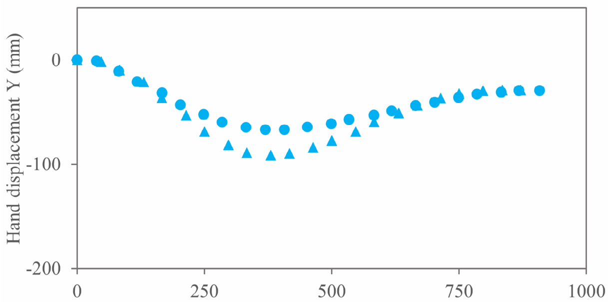
Fig. A.3. Subject #4 (●: 1st try, ▲: 2nd try).



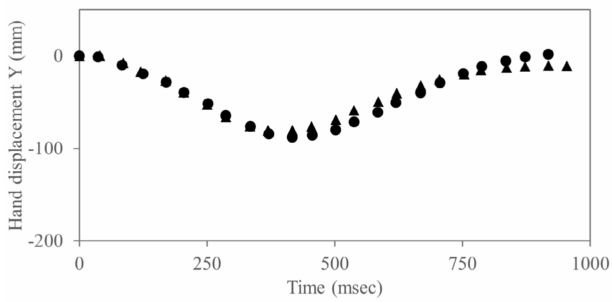
(a) Open eye tensed



(b) Close eye tensed



(c) Open eye relaxed



(d) Close eye relaxed

Fig. A.4. Subject #5 (●: 1st try, ▲: 2nd try).

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