Estimation and contribution of joint stiffness in musculoskeletal modeling of the thumb

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INTRODUCTION

Contrary to the four long fingers, musculoskeletal thumb models still failed in estimating reliable musculotendon forces. This was attributed to the complex anatomy and kinematics of the trapeziometacarpal joint (TMC) [1]. Because the TMC joint have been found to be often used near joint locks, we hypothesized that joint stiffness wich is currently ignored in hand musculoskeletal models should be integrated and may help to improve tendon forces estimates.

TMC joint stiffness results of the intricate combination of 16 ligaments, joint capsule, skin, joint contacts, and passive contributions of musculo-tendon system. Modeling each individual structure is thus a complex process submitted to large cumulative errors. Consequently, we choose to evaluate a global stiffness–posture relationship. The key aspect of this work was to estimate a passive moment–angle relationships reusable with anthropometric data set of tendon moment arms [2] which take into account of the interaction between the two Degrees of Freedom of the TMC.

METHOD

An external force was applied with six different force directions (-30°; 0°, 30°, 60°, 90°, 120° ; 0° meaning facing the palm of the hand) on the metacarpophalangeal joint of the thumb of nine participants using metallic rods disposed around the hand. Each rod was slid horizontally at controlled low speed by the experimenter to prevent any viscosity and damping effects. The external force applied was recorded using a 6 axes force sensor. Participants were instructed to stay relax, not to resist to the force application. Surface electromyography ensured inactivity of the muscle groups involved.

TMC was considered as a universal joint with two DoFs in flexion/extension (φ) and in adduction/abduction (θ) as in [2]. The 3D posture of the thumb was recorded by six infra-red cameras. Micro-reflective markers were fixed on the thumb metacarpal, dorsal hand plane and rod. The trapezium was positioned according to [2] and joint angles were computed using Eulerian angles. Passive moments were evaluated by inverse dynamics using external force, anthropometric and kinematic data.

Experimental results where then fitted with an exponential least square regression [3] to represent the subject mean behavior. The posture of TMC was further recorded during grasping various objects and the contribution of passive moments in the total moments at the TMC joint was calculated.

RESULTS AND DISCUSSION

For each subject, results consisted in two data sets: Mp_{Flex} and Mp_{abd} (Figure 1) respectively the passive moment of flexion and the passive moment of abduction, according to both TMC angles (φ and θ).

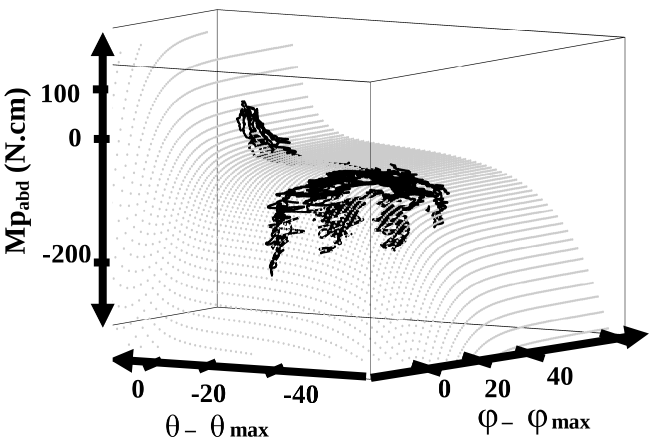

Figure 1: Moment of abduction according to the TMC angles (φ and θ). Bold grey represents the experimental data of one subject for all conditions as the light grey nap represents the exponential regression.

For each subject, the exponential regressions fitted well with the experimental data (mean RMSE= 23.6). Results showed a good agreement between subjects and the exponential regressions of the nine subjects were then averaged to provide a generic function of TMC joint stiffness. Equation 1 shows the form of the relation between Mp_{abd} and the TMC angles (φ and θ) as well as the coefficients estimated.

Equation 1:

$$Mp_{abd} = -71.9.\exp[-0.55.(\varphi - \varphi_{max})] + 31.91$$
$$- 4.49.\exp[-0.07.(\theta - \theta_{max})] - 110.6.\exp[0.39.(\theta - \theta_{max})]$$

The equation takes into account of the subjects own range of motion: φ_{max} and θ_{max}. The coefficients represent the mean behavior of the nine subjects.

From these results we found that the passive stiffness could contribute until 12% in the total moment of abduction during static gripping.

CONCLUSIONS

This study proposed a generic stiffness-posture relationship as well as an easy to use method to estimate global stiffness at individuals' complex joints. Results demonstrated that joint stiffness participate in equilibrating external forces (especially adduction/abduction forces) and should be included in thumb models. Integrating this relationship would influence tendons forces and may help predicting more realistic tendons forces.

REFERENCES

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