

Electronic Supplementary Materials 2 (ESM2) – Additional results and methodological details of the forehand motion capture protocol

This document is an electronic supplementary material (ESM2) for the article entitled “Electromyography-informed musculoskeletal modelling provides new insight into hand tendon forces during tennis forehand”

Article information

Electromyography-informed musculoskeletal modelling provides new insight into hand tendon forces during tennis forehand

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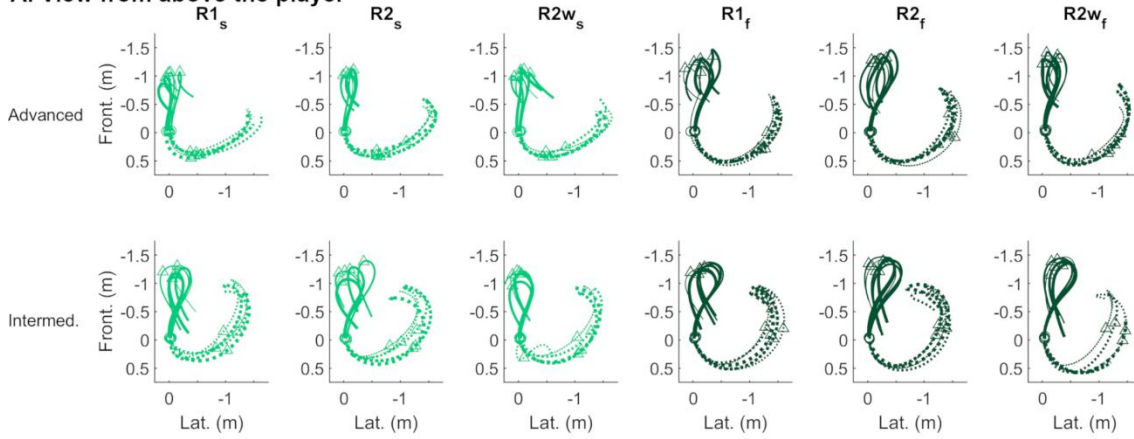
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Forehand additional results

Racket centre trajectory

A. View from above the player



B. View from right side of player

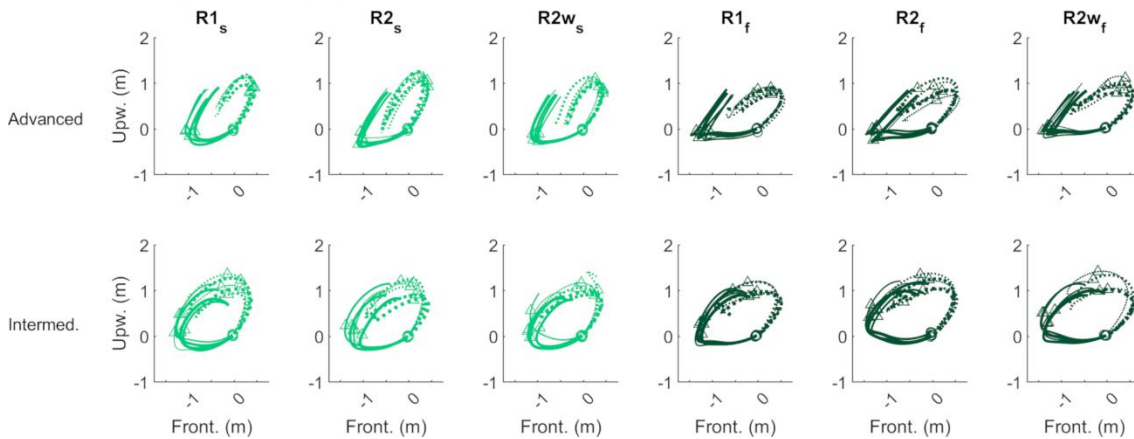


Figure s2-1. Racket centre trajectory from above (A) and from the right side of the player (B) for the Advanced and Intermediate player. Lateral axis is pointing toward the right side of the player (negative values correspond to the left). Frontal axis is pointing toward the target, anterior to the player (negative values correspond to posterior). Upward axis is pointing up (negative values corresponding to value below the ground).

Racket velocity and acceleration

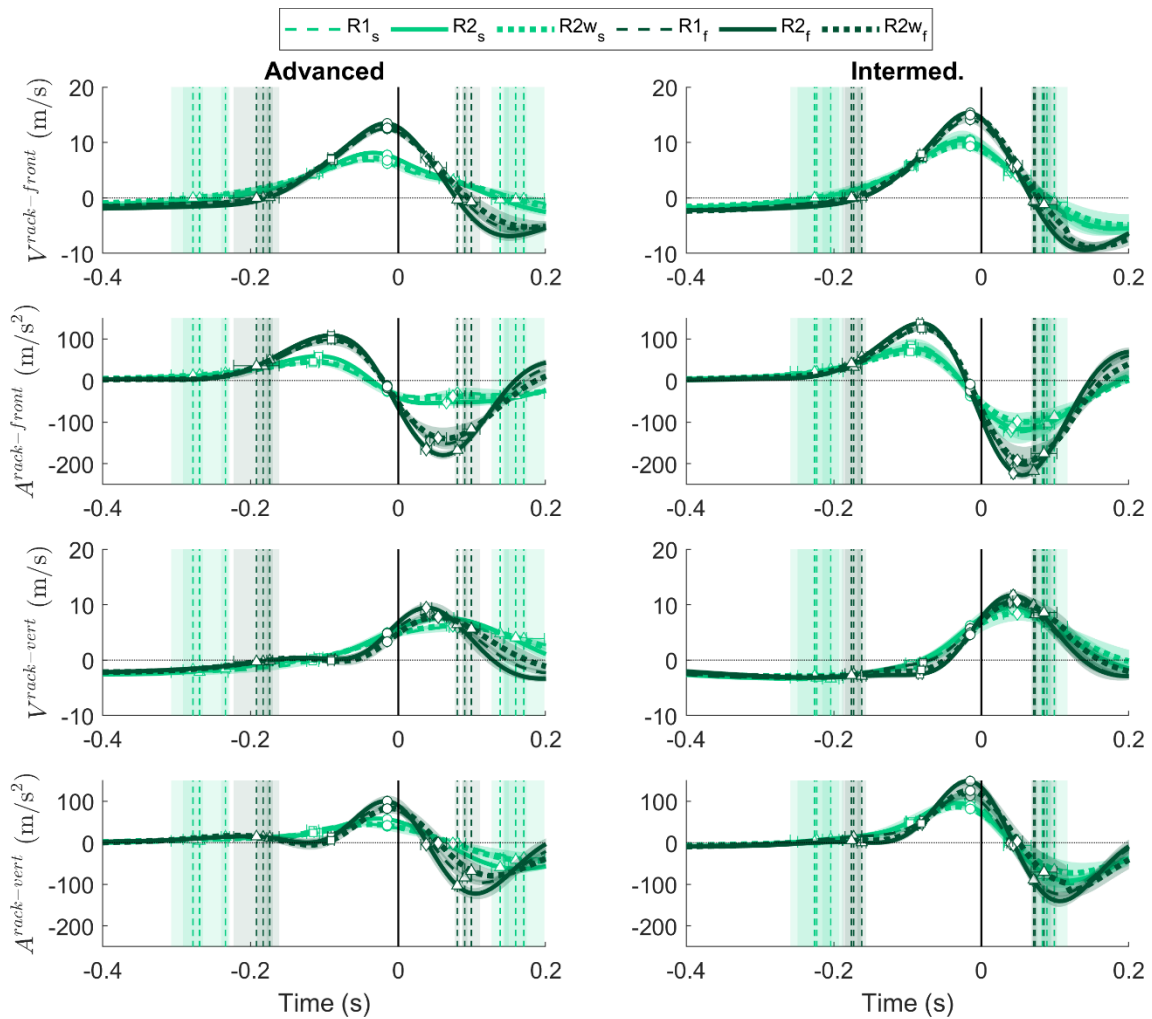


Figure s2-2. Mean time-patterns ($N=5$ trials) of racket velocities and accelerations during the forehand drive of both players (Advanced and Intermediate) for the two shot speeds (Slow, s ; Fast, f) performed with the three rackets (R1, R2, R2w). Shaded areas represent \pm one standard deviations around the mean. Lighter nuances represent the Slow (s) speed shots and darker nuances the Fast (f) ones. The vertical solid black bar represents the impact frame, the dashed vertical bars represent the beginning and end of forward acceleration phase, and the different points correspond to the frames on which musculoskeletal model was ran (see corpus of the article). $V^{\text{rack-front}}$: racket centre velocity along the frontal axis (pointing toward the target). $A^{\text{rack-front}}$: racket centre acceleration along the frontal axis. $V^{\text{rack-vert}}$: racket centre velocity along the vertical axis (pointing up). $A^{\text{rack-vert}}$: racket centre acceleration along the vertical axis. Racket centre is computed as the midpoint between lateral markers RK9D and RK9U (see details below).

Joint angles

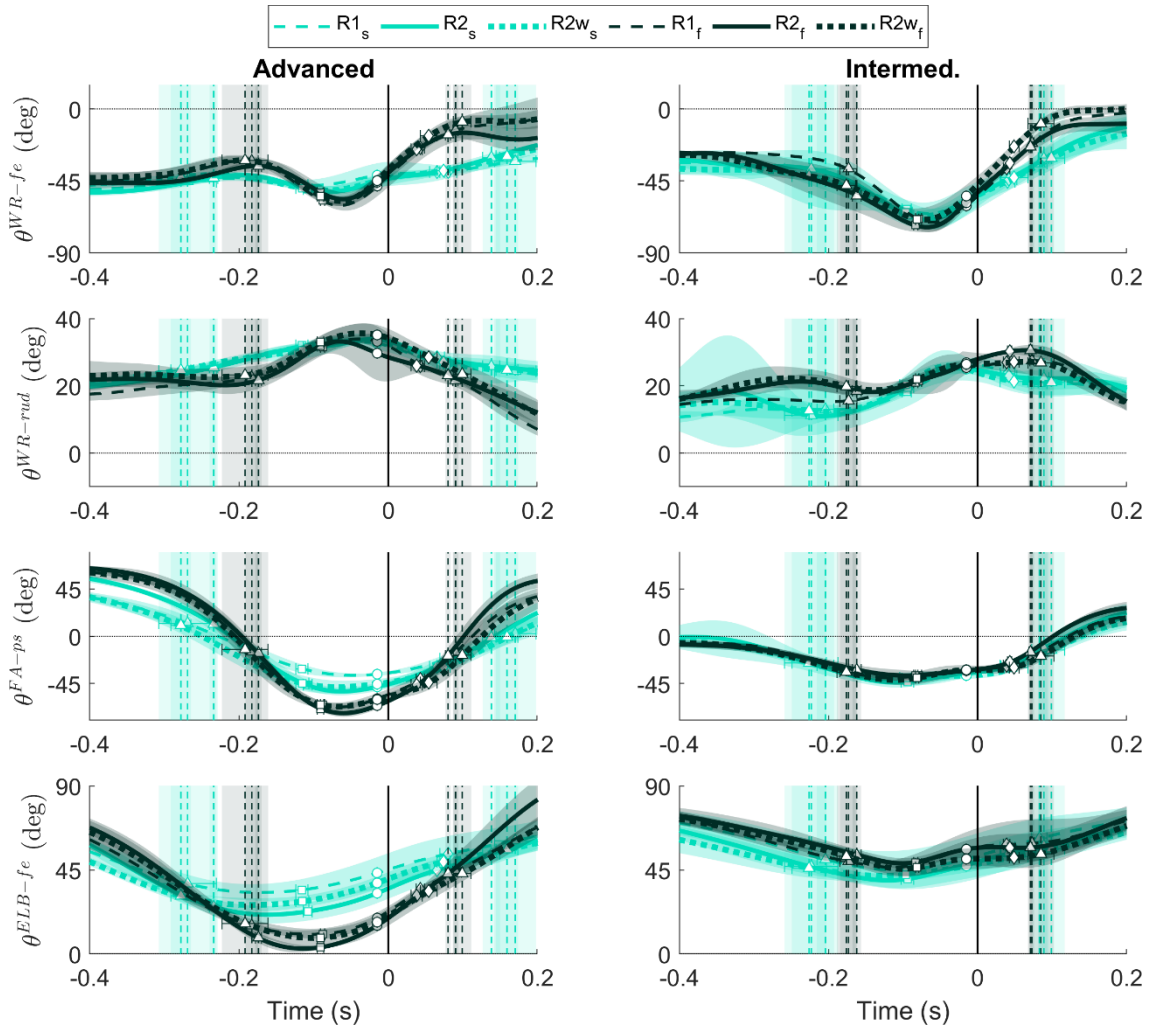


Figure s2-3. Mean time-patterns ($N=5$ trials) of racket velocities and accelerations during the forehand drive of both players (Advanced and Intermediate) for the two shot speeds (Slow, s ; Fast, f) performed with the three rackets ($R1$, $R2$, $R2w$). Shaded areas represent \pm one standard deviations around the mean. Lighter nuances represent the Slow (s) speed shots and darker nuances the Fast (f) ones. The vertical solid black bar represents the impact frame, the dashed vertical bars represent the beginning and end of forward acceleration phase, and the different points correspond to the frames on which musculoskeletal model was ran (see corpus of the article). θ^{WR-fe} : wrist flexion-extension, positive in flexion. θ^{WR-rud} : wrist radial-ulnar deviation, positive in ulnar deviation. θ^{FA-ps} : forearm pronation-supination, positive in supination. θ^{ELB-fe} : elbow flexion-extension, positive in flexion. See below for details on joint angle computation. Details on joint angle computation are provided below

Forehand motion capture methodological details

Marker placement

Upper limb segment kinematics were assessed using a seven-camera motion capture system (MX T40, Vicon, Oxford, UK) tracking 20 reflective markers with a 14-mm diameter that were placed on the right right upper limb. The arm was tracked by three markers placed on the acromion and both epicondyles as well as a supplementary one placed on the lateral aspect to control the internal rotation of the shoulder. The forearm was tracked with three markers placed on styloid and on the distal part of the radius. The hand was tracked by four markers placed on the dorsal aspect of metacarpals. The racket was tracked by 6 markers placed all around the frame.

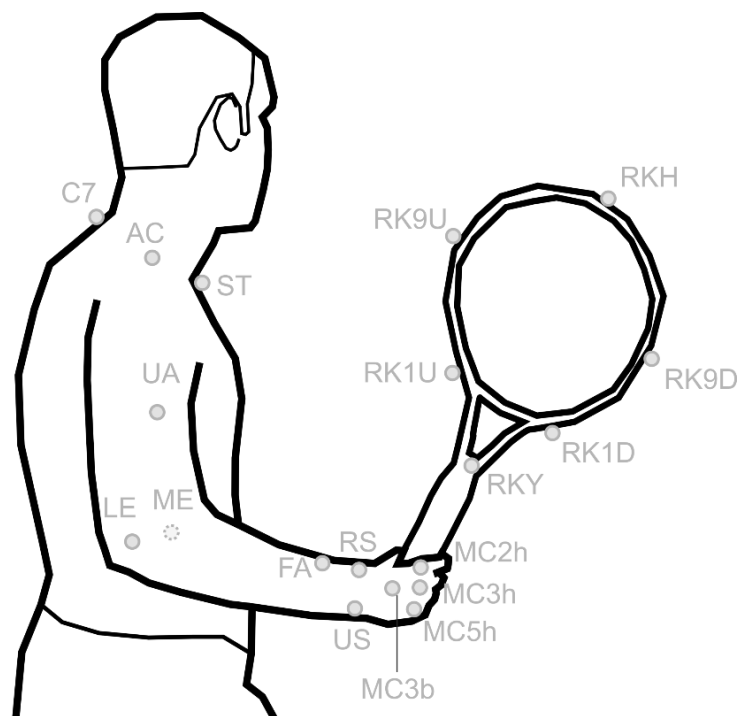


Figure s2-4. Illustration of the marker placement. See Table s1.1 for exact placement.

Joint angle computation

The upper limb joint angles were estimated from the filtered marker coordinates on the impact-centred window. For each trial, a 1.5-s analysis window centred around the ball impact time frame was first determined and kept for further analysis. The

impact frame was considered as the minimal 3D relative distance between the ball and the racket centre, calculated as the mean of the two side markers, using raw coordinates. The marker coordinates were low-pass filtered (Butterworth, 5Hz, order 2, zero-phase). At each time frame, segment coordinate systems were determined from filtered marker coordinates (Table s1.2).

Table s2-1. Name and locations of the markers used in the kinematic process.

| Name | Location |
|---------|--|
| Arm | |
| AC | Most dorsal point on the acromion prominence |
| LE | Most distal point on the lateral epicondyle |
| ME | Most distal point on the medial epicondyle |
| Forearm | |
| US | Most distal point on the ulnar styloid dorsal aspect |
| RS | Most distal point on the radial styloid dorsal aspect |
| FA | Three fingerbreaths in the proximal direction from RS along the radius |
| Hand | |
| MC3h | Most distal point on the 3 rd metacarpal head dorsal aspect while flexing metacarpophalangeal joint |
| MC3b | Three fingerbreaths in the proximal direction from MC3h along the i th metacarpal |
| MC2h | Most distal point on the 2 nd metacarpal head dorsal aspect while flexing metacarpophalangeal joint |
| MC5h | Most distal point on the 5 th metacarpal head dorsal aspect while flexing metacarpophalangeal joint |
| Racket | |
| RKH | Between the 8 th and 9 th main (longitudinal) string on the racket top |
| RK9U | At the level of the 9 th cross string on the side pointing down (floor) when the racket is at the impact while the Yoke marker pointing posterior |
| RK9D | At the level of the 9 th cross string on the side pointing up (ceiling) when the racket is at the impact while the Yoke marker pointing posterior |

Table s2-2 – Equations used to compute axes of segment coordinate systems

| | 1 st axis | 2 nd axis | 3 rd axis | Origin |
|----------------|-----------------------------------|--|------------------------------------|-----------------|
| Elbow | | | | |
| Humerus | $\vec{y} = \vec{u}_{(MidE,AC)}$ | $\vec{x} = \vec{y} \times \vec{u}_{(ME,LE)}$ | $\vec{z} = \vec{x} \times \vec{y}$ | MidE=0.5(LE+ME) |
| Forearm | $\vec{y} = \vec{u}_{(US,ME)}$ | $\vec{x} = \vec{y} \times \vec{u}_{(US,RS)}$ | $\vec{z} = \vec{x} \times \vec{y}$ | US |
| Forearm | | | | |
| Ulna | $\vec{y} = \vec{u}_{(US,MidE)}$ | $\vec{x} = \vec{y} \times \vec{u}_{(ME,LE)}$ | $\vec{z} = \vec{x} \times \vec{y}$ | US |
| RadiusFa | $\vec{y} = \vec{u}_{(RS,LE)}$ | $\vec{x} = \vec{y} \times \vec{u}_{(US,RS)}$ | $\vec{z} = \vec{x} \times \vec{y}$ | RS |
| Wrist | | | | |
| Radius | $\vec{y} = \vec{u}_{(RS,FA)}$ | $\vec{x} = \vec{y} \times \vec{u}_{(US,RS)}$ | $\vec{z} = \vec{x} \times \vec{y}$ | RS |
| Hand | $\vec{y} = \vec{u}_{(MC3h,MC3b)}$ | $\vec{x} = \vec{y} \times \vec{u}_{(MC2h,MC3h)}$ | $\vec{z} = \vec{x} \times \vec{y}$ | MC3h |
| Syst. Dynamics | | | | |
| Hand-Racket | $\vec{y} = \vec{u}_{(MC2h,MC3b)}$ | $\vec{x} = \vec{y} \times \vec{u}_{(MC2h,MC5h)}$ | $\vec{z} = \vec{x} \times \vec{y}$ | MC3h |

$\vec{u}_{(P1,P2)}$ represents the unit vector associated to the vector going from point P1 to P2. Radius1 and Radius2 are two different coordinate systems used for computation of pronation-supination and wrist joint angles, respectively. Hand-Racket corresponds to the coordinate system used to compute the acceleration of the hand-racket system in the global coordinate system.

For all segments, three axes were computed with first the longitudinal (\vec{y}) axis as the unit vector from the distal to the proximal marker, thus pointing in the proximal direction. The second axis was the transverse (\vec{x}) axis, pointing in the dorsal direction,

and was orthogonal to the plane defined by \vec{x} and a vector pointing radially. The third axis was the sagittal (\vec{z}) and was the cross product of the two others. The definition for the Humerus, Forearm, Ulna and Radius1 to compute elbow and prono-supination were taken from Wu *et al.* (2005)

The joint angles were extracted from relative orientation matrices using Cardan sequences. The elbow rotations were extracted from the orientation of the Forearm segment relatively to the Humerus with a z-x-y (flexion-rotation-abduction) sequence but only the flexion/extension joint angle was kept. The forearm pronation-supination rotation was extracted from the orientation of the RadiusFa segment relatively to the Ulna using a x-z-y (abduction-flexion-pronation) sequence. The wrist rotations were extracted from the orientation of the Radius segment relative to the Hand using a z-y-x (flexion-rotation-deviation) and both flexion-extension and radial-deviation were kept.

References

Wu, G., van der Helm, F. C. T., Veeger, H. E. J. D., Makhsous, M., Van Roy, P., Anglin, C., Nagels, J., Karduna, A. R., McQuade, K., Wang, X., Werner, F. W., & Buchholz, B. (2005). ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion--Part II : Shoulder, elbow, wrist and hand. *Journal of Biomechanics*, 38(5), 981-992.