



Vibration-Damping technology in tennis racquets: Effects on vibration transfer to the arm, muscle fatigue and tennis performance



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ABSTRACT

High vibration transfer from a tennis racquet to the player may cause discomfort, and is hypothesized to influence performance and the onset of muscle fatigue. This study examined a racquet with a novel vibration damping technology (VDT) designed to mitigate frame vibration. Racquet vibration, post-impact vibration transfer to the player, arm electromyographic activity and tennis performance were compared to a non-VDT racquet. Nineteen young adult, competitive tennis players hit forehands and serves until near exhaustion on two days; using one of the two racquets each day. Tri-axial accelerometers mounted to racquet shaft, hand and forearm recorded vibration behaviour. Surface electromyography recorded activity of five arm muscles. In comparison to the non-VDT racquet, the VDT design showed: 1) A significantly lower mean normalised acceleration signal energy at the racquet during unfatigued play (−40%) and at *near exhaustion* (−34%), which corresponded to a 20–25% lower signal energy at the hand. 2) Reduced signs of arm muscle fatigue at *near exhaustion*, which was most pronounced in biceps and wrist extensors. 3) Players hit 11% more forehands and placed 40% more hits in the target area at *near exhaustion*. Conclusion: VDT effectively reduces racquet vibration. Initial evidence indicates that it may delay muscle fatigue, which was associated with increased ball placement accuracy.

Introduction

In tennis, the impact of a ball hitting the racquet induces mechanical vibrations of the racquet. This vibration is transmitted along the racquet frame to the hand and the forearm of the player.¹ Immediately after ball impact, wrist extensor muscles show the highest activation of the major arm muscles in an attempt to stabilize the wrist.² Players can modulate vibration transfer to their hand/arm by adjusting the location of ball impact^{3,4} or their grip force.^{1,5,6}

Recognizing that post-impact tennis racquet vibrations may cause player discomfort, manufacturers have introduced measures to minimize mechanical vibration. For example, string vibration dampers were promoted to reduce overall string vibration and thereby racquet frame vibration. String vibration damping was thought to be an effective tool to decrease discomfort without degrading performance as higher string tension improves hitting accuracy, but also increases the shock associated with ball impact.¹ However, the available evidence on their

effectiveness in reducing vibration transfer to the hand/arm is at best inconclusive. They only dampen the audible frequencies of the strings (>200 Hz), but do not attenuate the lower-frequency vibration of the frame that is in the range of 80–200 Hz.^{7,8} In addition, there is no evidence that they effectively dampen vibration amplitude at the wrist or elbow.^{8,9} Other technologies aimed to reduce vibration of the racquet itself. For example, a self-powered piezoceramic fibre system that stores energy from the ball impact and then generates a counter-vibration mechanical force was introduced. It reduced vibration of a freely suspended racquet by 50%.^{10,11} Subsequent field-testing showed reduced severity of acute tennis elbow symptoms in adult recreational players after 12 weeks of racquet in comparison to a control group who experienced similar symptoms, but used a traditional, non-piezoceramic racquet design.¹²

However, the potential health benefits of low vibration racquets in preventing common forms of tennis related injury such as lateral epicondylalgia at the elbow are largely unproven. Other contributors to

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tennis elbow symptoms, such as maladaptive strategies for the dynamic stabilization of the wrist joint, prolonged activation and repetitive loading of the wrist muscles and tendons during play,^{13,14} and the forced eccentric stretch of forearm muscles created by the initial shock of impact, are not addressed by reduced racquet frame vibration.¹⁵ Despite the limited evidence that frame vibration is a mechanism of overuse injury, manufacturers remain interested in designing low vibration racquet frames, because the prolonged exposure to high vibrations may cause discomfort. Ultimately, they can affect game performance.

It is known that the mechanical vibrations of the racquet transferred to the human body are largely absorbed by soft tissue. Peak-to-peak acceleration and signal energy measured at the racquet is attenuated four-to six-fold at the wrist^{4,5,16} and becomes further reduced when transferred from the wrist to the elbow.^{5,17} It is less well understood how a reduced level of vibration transfer to the arm affects the underlying muscle activity needed to stabilize the wrist and elbow during play.

It would be especially relevant to understand, whether VDT preserves arm muscle activity when a player becomes fatigued. In addition, it would be useful to know, if a VDT racquet allows players to maintain their initial performance level towards the end of a game. Thus, the purpose of this study was to document the effects of VDT in tennis racquets by measuring 1) the vibration behaviour at the racquet, 2) the vibration experienced at the hand and forearm (i.e. the vibration transfer), 3) the associated electromyographic (EMG) patterns of arm muscle activity and 4) indicators of tennis performance, such as ball speed or ball placement accuracy. A cohort of highly trained tennis players tested a newly designed VDT racquet and a comparable non-VDT racquet. Performance was evaluated at the beginning of play (*baseline*) and at the level of perceived exertion before the termination of play (here termed *near exhaustion* state). We hypothesized that compared to the non-VDT racquet, the use of VDT racquet would result in lower vibration at the racquet, lower vibration experienced at the hand and forearm. Moreover, when comparing the performance at the *baseline* and *near exhaustion* states, use of a VDT racquet would be associated with lower levels of muscular fatigue and reduced decline in tennis performance when reaching *near exhaustion*.

Material and methods

Study design and racquet characteristics

The study employed a single-group crossover design in which each player tested both racquets on two separate days, one on each day. Players were pseudo-randomly assigned to use either the VDT racquet or the non-VDT racquet in the first session. They then rested for at least 24 h before using the other racquet in a second session. Both racquets were provided by the Wilson Sporting Goods Company (Chicago, Illinois, U.S.A.). They were manufactured using the same methods. The two racquets looked identical in appearance, had the same mass (319 g), centre of mass (335.7 mm from the base of the racquet handle), stiffness (4430 N/m), head area (98 square in.) and exhibited comparable fundamental frequencies (VDT racquet: 130 Hz; non-VDT racquet: 134 Hz). Both racquets were strung with the same string pattern (18 main and 20 cross strings), string type (Luxilon 4G 125) and string tension (60lbs = 266.90 N). The only difference in the VDT racquet was the inclusion of a layer of composite material in the frame. The composite materials combines a traditional damping layer with a layer of fibre preform. It aims to maximize the dissipation of mechanical energy into the surrounding polymeric materials. The material is commercially known as Countervail® (Materials Sciences Corp., Horsman, Pennsylvania, U.S.A.). The VDT racquet is identical to the 2017 model Wilson Blade. The non-VDT racquet had been commercially available since 2015. Players were naïve about the differences between the racquets.

Participants

Nineteen healthy, young adult, right-handed tennis players (10 men, 9 women, $M_{age} = 21$ years 5 months, $SD \pm 2$ years 9 months) participated. All participants were Division 1 players of the University of Minnesota Varsity team. They had played a minimum of 3 years at this collegiate level. All participated in regular training throughout the year (at least 3 h per week), and had competed in intercollegiate, national and international tournaments. All participants consented to participate in the study prior to the data collection. The study protocol was approved by the Institutional Review Board of University of Minnesota. No participants reported any musculoskeletal or neurological impairment in the past 6 months prior to study participation.

Apparatus and experimental setup

A wearable 16-channel system (DataLOG MWX8, Biometrics Ltd., Newport, United Kingdom) recorded signals from three tri-axial accelerometers (Model: S3-1000G-HA, Biometrics Ltd., Newport, United Kingdom) and five bipolar surface EMG channels. Each tri-axial accelerometer had an amplitude range of ± 1000 g. Acceleration signals were sampled at 5 kHz. Accelerometers were secured to the shaft of the racquet, right above the handle grip tape, and on the dorsal side of the forearm (at proximal 1/3 of forearm, avoiding forearm muscle bulk) and hand (midpoint of the 3rd metacarpal bone) (Fig. 1). The accelerometer on the racquet was fastened by a screw to the racquet to ensure tight mechanical coupling. The accelerometers on the hand and forearm were

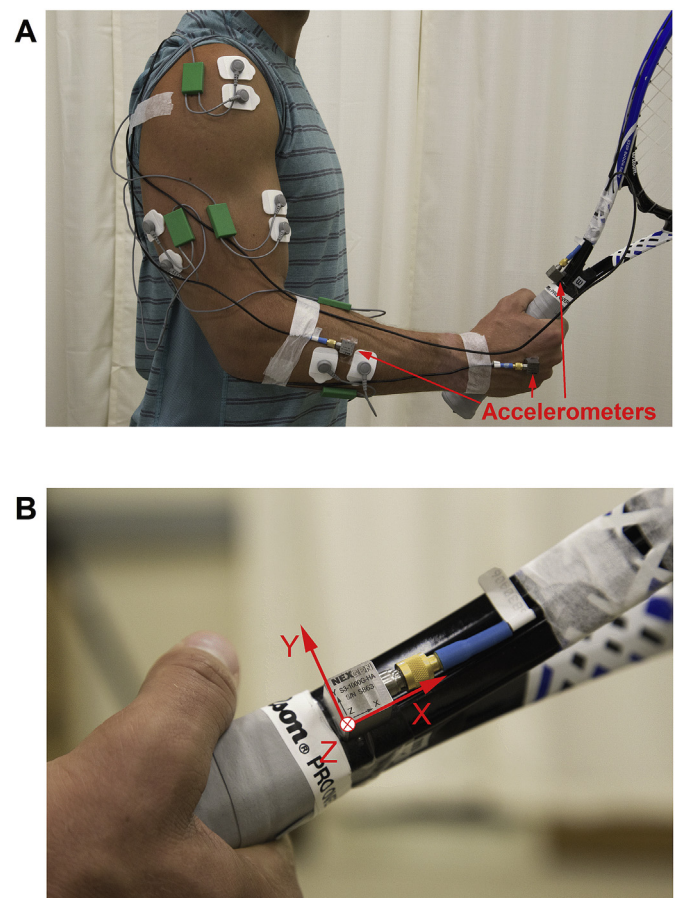


Fig. 1. Experimental setup. (A) Surface EMG electrodes were placed on the anterior deltoid, biceps brachii, triceps brachii, wrist extensors and wrist flexors (not shown in the picture). Accelerometers were secured on the racquet shaft, the dorsal side of the hand and forearm. (B) The coordinate system of a tri-axial accelerometer.

attached using double-sided tape and were further secured with elastic self-adherent wrap to minimize movement-related artefacts. Surface EMG of wrist flexors, wrist extensors, biceps brachii, triceps brachii and anterior deltoid were recorded at a sampling rate of 1 kHz using the same 16-channel wearable system (Surface EMG Amplifier Model: SX230FW, Biometrics Ltd., Newport, United Kingdom). Electrode placement followed the SENIAM recommendation for deltoid, biceps and triceps and the recommendation by Criswell for the wrist muscles.¹⁴ EMG electrodes were also secured with elastic self-adherent wrap. A TrackMan Doppler Radar system (TrackMan Inc., Stamford, U.S.A.) recorded ball speed, distance of the ball, and its angular position in the transverse and sagittal plane at a sampling rate of 100 Hz. TrackMan reports the accuracy of an earlier model to be less than 0.3048 m (1 ft) at a distance of 30.48 m (100 yards) or 0.33% accurate. An independent study established positional accuracy of the radar system used in this study to be 0.7% accurate with respect to a range finder. Speed was 2.3% accurate with respect to the speed calculations based on a high speed video tracking system.¹⁸ Accelerometers, EMG and the TrackMan system recorded continuously throughout testing. Players used a hand-held dynamometer (TSD121C, BIOPAC Systems Inc., Galeta, CA, U.S.A.) to obtain a measure maximal voluntary grip strength before and after the play.

Procedure

All testing took place on an indoor tennis hard court of the University of Minnesota Tennis Centre. Before the data collection, participants warmed up properly either with another player or with a ball machine. Two baseline assessments were performed prior to testing: 1) maximal voluntary grip strength was measured in three repetitions with participants standing, wrist slightly extended, elbow flexed at 90° and the upper arm adducted against the torso, and 2) maximal voluntary isometric contractions (MVIC) for each of the five recorded muscle groups. During the MVIC testing, participants performed maximal contraction at the respective muscle group against the resistance provided by an experimenter. Two experimenters performed MVIC testing for all the participants. Each participant had the same experimenter perform the pretest and posttest. Three repetitions for each muscle group were performed with each repetition lasting for 3 s with 5-s breaks in between repetitions.

Data collection for each session consisted of three blocks (Fig. 2). In each block, the participant performed varying number of serves and forehand strokes. One-minute breaks were given between blocks. After every 15 hits, participants reported their perceived level of exertion using the Borg Rating of Perceived Exertion Scale (RPE),¹⁹ which ranges from 6 (*no exertion*) to 20 (*maximal exertion*). Players stopped playing when they reached a perceived exertion level of 18 on the Borg RPE scale, rated as being between *very hard* and *extremely hard*.

Block 1 began with 15 serves and was followed by 45 forehand strokes to return balls launched by the ball machine aimed at the centre mark every 2 s to a targeted corner in the opposite court. The target ball landing area was a marked 2 m × 2 m square area bordering the service line and singles sideline on both sides of the court. Participants were instructed to land the return balls within either of the target area. Block 2 started with 30 serves followed by 90 forehand strokes. Participants

served or returned towards the left and right targeted area alternatively. In Block 3 participants served or returned towards the left and right targeted area in a randomized order. A research staff in the opposite court signalled the target area for each hit. In this block, participants first performed 45 serves, and then continued with forehand strokes until they reached level 18 on the Borg RPE scale. Immediately following the cessation of the play, participants completed a posttest of grip strength and MVIC that was identical to the pretest protocol described above. The total playing time of each player was approximately 30 min.

Measurements

To analyse the effects on vibration behaviour of the racquet, vibration transfer and muscular fatigue, two separate states were defined: *baseline* and *near exhaustion*. The *baseline* state included 10 forehands (the 5th to 14th) in the first block. The first four strokes were skipped to avoid confounds due to potential initial fluctuations in the ball speed of the ball machine or because players may need a few strokes to settle into the task. The *near exhaustion* state included 10 hits (12th last to 2nd last) just before participants reached perceived exhaustion (i.e. level of 18 on the Borg RPE scale). Vibration behaviour, vibration transfer and EMG activity were evaluated only during the baseline and near exhaustion states. Indicators of tennis performance (number of hits completed, ball speed and ball placement accuracy) were recorded throughout the play by the TrackMan Doppler Radar system. All mechanical and electrophysiological variables were derived from their respective raw time-series data using custom written routines based on MATLAB Technical Programming Language.

Peak acceleration and acceleration signal energy at the racquet, hand and forearm

The first peak acceleration after ball impact at the racquet, hand and forearm served as a marker of initial shock. Acceleration signal energy at the racquet, hand and forearm after the peak acceleration indicated racquet vibration and the associated vibration experienced at the hand and forearm. Following established signal processing protocols, the acceleration signals along the x, y and z axes for each accelerometer were filtered using a 4th order Butterworth band-pass filter with a passband of 20–950 Hz. The 20 Hz high pass cut-off frequency was used to remove the influence of arm movement on the acceleration signals.^{5,16} The upper limits of the filter conformed to the known tennis racquet vibration content⁸ as well as to avoid any signal distortion near the accelerometer resonance frequency (>30 kHz). The acceleration signals from the three channels were processed separately. For each stroke, the peak acceleration was determined. Subsequently, mean peak acceleration across 10 strokes was computed for each state (*baseline* and *near exhaustion*).

For the same 10 forehand strokes at *baseline* and *near exhaustion*, we derived acceleration signal energy at the racquet, hand and forearm. Acceleration signal energy was computed as the sum of the squares of the acceleration for 500 samples (i.e. 100 ms) after the peak acceleration for x-axis, y-axis and z-axis during each forehand stroke. Mean acceleration signal energy for 10 strokes (ASE_{10}) was computed for each participant using the following equation⁵:

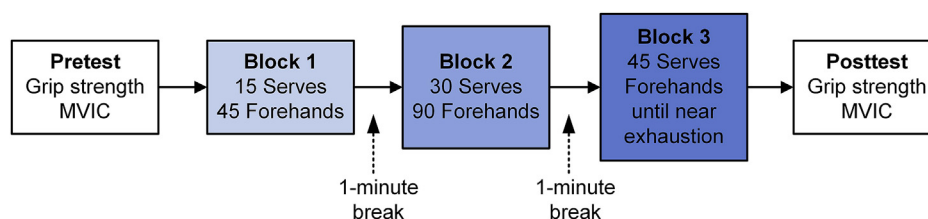


Fig. 2. Experimental protocol for a single testing session. Participants rested for 1 min between blocks. Block duration increased steadily between blocks as players needed to hit more balls. In Block 3 forehand strokes were performed until the near exhaustion state was reached. All participants conducted two sessions on two separate days. Each day they tested only one of the two racquets (either VDT or non-VDT racquet).

$$ASE_{10} = \frac{\sum_{i=1}^{10} \sum_{n=1}^{500} |a_i(nT_s)|^2}{10} \quad (1)$$

where i = number of forehand strokes, n = number of samples, a_i = instantaneous acceleration at time, and T_s = sampling interval = 0.2 ms. To account for the initial shock of ball impact and for individual differences in peak acceleration between players, we normalised acceleration signal energy by computing the ratio between resultant ASE_{10} and the mean resultant peak acceleration for each participant and report this variable as *normalised resultant* ASE_{10} .

Measuring tennis racquet vibration

To assess the effect of VDT on racquet frame vibration in isolation when no player is handling the racquet, Experimental Modal Analysis was used to extract peak acceleration and acceleration signal energy of both racquets when they were freely suspended along their longitudinal axis using the setup suggested by Russell.²⁰ Acceleration was measured at the racquet neck (accelerometer placement was identical to the human testing; see Fig. 1). An impact hammer contacted the racquet at the same impact point (centre of the 6th string counting from the head of the racquet) for five trials for the VDT and non-VDT racquets. The force and acceleration time-series signals were sampled at 5 kHz.

Changes in muscle activity and grip strength as indicators of muscle fatigue

To understand the effects of VDT on muscle activation and muscular fatigue at *near exhaustion*, we recorded muscle activity of five major arm muscle groups (wrist flexors, wrist extensors, biceps brachii, triceps brachii and anterior deltoid, see Fig. 1). The EMG signals were filtered using an 8th order band-pass Butterworth filter with a passband of 10–490 Hz and subsequently full-wave rectified. Root mean square smoothing with a window of 100 ms was additionally applied to EMG signals obtained during MVIC testing. Average peak EMG activity during the three recorded MVICs of each muscle group at pretest was used to normalise the EMG signals during *baseline* and *near exhaustion* states, i.e. expressed as a percentage of pretest MVIC. To obtain a global measure of the amount of muscle activity over time, integrated EMG activity (IEMG) at *baseline* and *near exhaustion* was computed for each stroke of the 10 strokes at each state using Equation (2):

$$IEMG = \frac{\sum_{n=1}^N \left| \frac{m(nT_s) * 100\% * T_s}{MVIC} \right|}{NT_s} \quad (2)$$

where m = instantaneous muscle activity, $MVIC$ = average peak EMG activity during MVIC at pretest, T_s = sampling interval = 1 ms, NT_s = total time for 10 forehand strokes. The onset and offset thresholds for IEMG computation were 5% of the average peak EMG of each stroke over the 10 strokes. To quantify the change of muscle activity from the baseline to near exhaustion states, the IEMG Ratio was calculated subsequently for each muscle group using Equation (3):

$$IEMG \text{ Ratio} = \frac{IEMG_{near \text{ exhaustion}}}{IEMG_{baseline}} \quad (3)$$

An IEMG Ratio of 1 means that muscle activity at *near exhaustion* is the same as the activity during *baseline* (i.e. no sign of fatigue). A ratio above 1 represents muscle activity that is greater at *near exhaustion*, indicating that the muscle recruited more fibres to produce similar work. This phenomenon is observed after prolonged muscle activation, but before the muscle fully fatigues. An IEMG ratio below 1 indicates that a muscle is close to full exhaustion and can no longer recruit sufficient number of fibres representing physiological muscle fatigue.

In addition, the median power frequency of the MVICs before and after the tennis play was computed to obtain a second marker of muscle fatigue based on the analysis of isometric contractions. Specifically, the power spectral density estimate was derived using a discrete Fourier transform and following Welch's method of overlapping segment

averaging (up to eight segments with a 50% overlapping Hamming window). The median power frequency represented the frequency where the power below that frequency was equal to or exceeded half of the total power when increasing the frequency from its lowest value. The average median power frequency (f_{MVIC}) was determined based on each of the three sets of MVICs before and after the cessation of tennis play. A decrease in the median frequency has been documented to be associated with muscular fatigue.²¹ Only the wrist flexors and extensors were analysed, because as wrist stabilisers, they were more likely to show signs of muscular fatigue than the proximal muscles.

Isometric grip force was recorded with a dynamometer before and after the cessation of tennis play as a third biomechanical marker of muscle fatigue. Mean peak grip force (F_{grip}) during a 3-s maximal effort contraction over the three trials before and after testing was computed.

Markers of tennis performance

Three markers of player performance were monitored: the total number of hits until perceived exhaustion, maximum ball speed, and the accuracy of ball placement with respect to the target ball landing area. Players were instructed to hit the ball into marked 2 m × 2 m square areas bordering the service and singles side lines on both sides of the court. Accuracy of ball placement was defined as the number of hits that landed within the target area for the first 8 hits at the *baseline* and the last 8 hits at the *near exhaustion* state. Research staff tracked the total number of balls hit during each block using a hand-held mechanical clicker counter. Maximum ball speed was obtained through the TrackMan system.

Adjusted sample size, outlier analysis and normality of data

This study collected large data sets on both serve and forehand strokes. It is beyond the scope of a single paper to provide detailed information on both. Given that one aim of the study was to investigate the effects of VDT at *near exhaustion*, the results presented here focus on the analysis of forehand strokes, because the last strokes before reaching a near exhaustion state were forehand returns for all participants.

We obtained incomplete data sets for three of the 19 tested participants due to the accidental shut-off of the data acquisition unit worn by participants around the waist or EMG electrodes losing contact with skin after heavy sweating. We decided to exclude the incomplete acceleration and EMG data for these three participants from further analysis, while we kept the complete data sets for grip strength and Track Man based tennis performance variables, which were recorded by separate systems. Before performing statistical comparisons, an outlier analysis was performed to identify potential outliers for all variables. Any values above or below 1.5 inter-quartile range from the first or third quartiles respectively were considered as outliers and were excluded from further analysis.²² Not more than three outliers were identified for each of the reported variables. After removing outliers, all variables were tested for normality using Shapiro-Wilk's test. Given that some variables had distributions significantly different from the normal distribution, we here report medians and inter-quartile ranges unless otherwise specified. Consequently, we applied non-parametric tests for comparisons across all variables to assure consistency. The significance level was set at 0.05. To account for the inflation of Type I error, the significance level values were adjusted using the Benjamini-Hochberg method with a false discovery rate at 5% for accelerometer measurements.^{23,24}

Results

Initial shock and vibration behaviour at the racquet

At free suspension, mean resultant acceleration signal energy of the VDT racquet after its strings were hit by the impact hammer was 74% lower when compared to the non-VDT racquet ($M \pm SD$ VDT: $0.88 \pm 0.29 \text{ g}^2$; non-VDT: $3.40 \pm 1.53 \text{ g}^2$; $z = 2.2$, $p = 0.032$; effect size: $d = 2.29$). The mean of the impact hammer striking force ($M \pm SD$ VDT:

5.58 ± 0.55 N; non-VDT: 6.10 ± 0.57 N), as well as the magnitude of initial shock as expressed by the mean resultant peak acceleration was not significantly different between the two racquets ($M \pm SD$ VDT: 1.43 ± 0.16 g; non-VDT: 1.47 ± 0.17 g; p 's > 0.05).

An example of the mechanical behaviour when a ball made contact with the racquet while handled by a player is shown in Fig. 3. In order to examine, if the two racquets mechanically behaved differently at *baseline* or *near exhaustion*, and to illustrate to what extent vibrations at the racquet were attenuated at the hand and forearm, we first analysed the mean peak accelerations at the racquet, hand and forearm at both states in all three directions (see Table 1). Across all players, mean peak acceleration at the racquet shaft ranged between 56–140 g along the longitudinal axis of the racquet (x-axis), 213–389 g for the axis perpendicular to the racquet head (y-axis - in the direction of ball impact), and 77–127 g in the vertical (z-axis). At *baseline*, individual mean peak acceleration showed the largest difference between the racquets in the longitudinal axis (x-axis). Mean x-axis peak acceleration of the VDT racquet was significantly lower (-16.2%) when compared to the non-VDT racquet ($z = 3.11$, $p = 0.002$) (see Table 2).

The corresponding ASE₁₀ expresses vibration over a 100-ms time window representing a global measure of vibration exposure (see equation (1)). We found that ASE₁₀ at the racquet at *baseline* was significantly lower for the VDT racquet when compared to the non-VDT racquet in two directions (see Table 3 and Fig. 4). With respect to the non-VDT racquet, ASE₁₀ at the VDT racquet was 30% lower along the longitudinal axis (x-axis). The difference reached statistical significance ($z = 2.78$, $p = 0.005$; see Table 3).

To account for the initial shock of ball impact and for individual

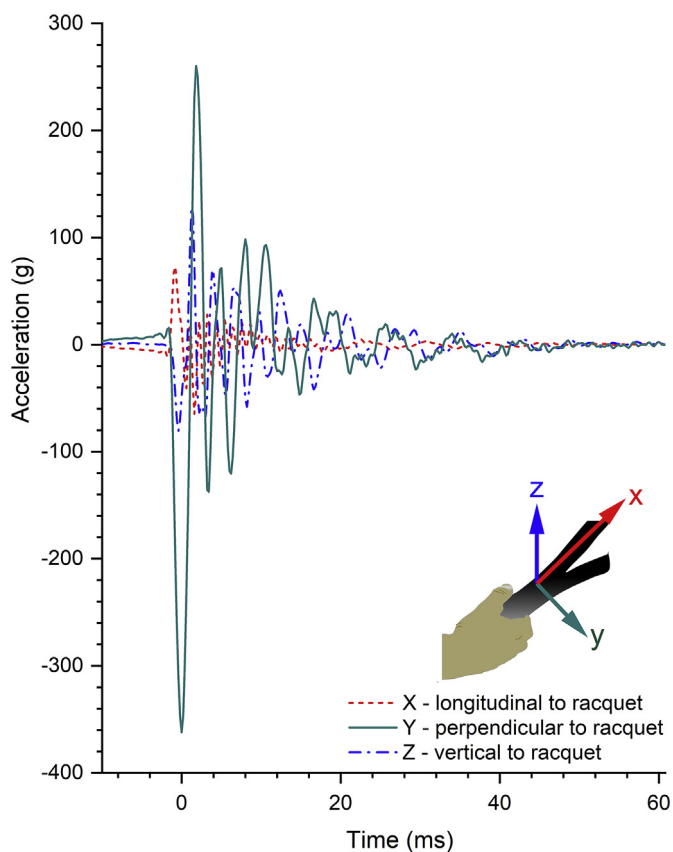


Fig. 3. Exemplar acceleration time series data measured at the racquet shaft of one participant using the VDT racquet during one forehand stroke. Shown are the three channels of the tri-axial accelerometer. The y-axis channel measured the acceleration perpendicular to the string surface and consequently revealed the highest accelerations. Time zero indicates the time of peak acceleration in the y axis after impact. Unit of acceleration is $g = 9.81 \text{ m/s}^2$.

Table 1

Mean peak acceleration and acceleration signal energy from five trials of hammer impact on freely suspended racquets. Values in parentheses represent one standard deviation. $g = 9.81 \text{ m/s}^2$.

Axis	Peak acceleration (g)		Acceleration signal energy (g^2)	
	non-VDT	VDT	non-VDT	VDT
X	0.27 (0.06)	0.23 (0.08)	2.98 (1.25)	1.08 (0.46)
Y	1.08 (0.12)	0.98 (0.12)	3.33 (1.49)	0.83 (0.21)*
Z	0.39 (0.09)	0.27 (0.04)	3.28 (2.01)	0.73 (0.22)*
Resultant	1.47 (0.17)	1.43 (0.17)	3.41 (1.53)	0.88 (0.29)*

Note. See Fig. 1B for orientation of the acceleration axes x, y, and z.

* $p < 0.05$ between the two racquets indicated by Mann-Whitney U test.

differences in peak acceleration between players, we normalised acceleration signal energy by computing the ratio between resultant ASE₁₀ and the mean resultant peak acceleration for each participant. Subsequent analysis revealed significant differences in the vibration behaviour of both racquets. At *baseline*, normalised resultant ASE₁₀ (Fig. 5) for the VDT racquet was 40% lower in comparison to the non-VDT racquet ($M \pm SD$ VDT: 1828 ± 217 g^2/g ; non-VDT: 3066 ± 1221 g^2/g ; $z = -3.24$, $p = 0.001$). At *near exhaustion*, normalised resultant ASE₁₀ for the VDT racquet was 34% lower ($z = -1.99$, $p = 0.046$).

Vibration transfer to the hand and forearm

As expected, vibration was markedly attenuated at the forearm and hand. Based on the pooled data of both racquets, the mean resultant peak acceleration was reduced by 45.2% (SD ± 36.2%) at the hand and 95.6% (SD ± 1.1%) at the forearm with respect to the racquet. Comparing signal attenuation between racquets showed that mean resultant peak acceleration at the hand was not statistically different at either the *baseline* or *near exhaustion* state (VDT_{baseline}: 41.2 g; non-VDT_{baseline}: 40.0 g; VDT_{near exhaustion}: 30.5 g; non-VDT_{near exhaustion}: 32.6 g; p 's > 0.05). The analysis of normalised resultant ASE₁₀ yielded similar results. Normalised resultant ASE₁₀ at the hand for the VDT racquet was 20.2% lower than for the non-VDT racquet at *baseline* ($M \pm SD$ VDT: 1057 ± 365 g^2/g , non-VDT: 1325 ± 638 g^2/g ; effect size: $d = 0.52$). At *near exhaustion*, normalised resultant ASE₁₀ at the hand for the VDT racquet was 25% lower than for the non-VDT racquet at *baseline* ($M \pm SD$ VDT: 813 ± 228 g^2/g , non-VDT: 1084 ± 521 g^2/g ; effect size: $d = 0.67$). However, given the large variability seen in the non-VDT racquet, both differences failed to reach statistical significance (p 's > 0.05). Finally, normalised ASE₁₀ (Fig. 5) at the forearm was not significantly different between the two racquets in either state (p 's > 0.05). The respective data are shown in.

Muscle fatigue measured by EMG activity and grip strength

Fig. 6 shows a typical arm muscle activation pattern associated with the return of a ball during a forehand stroke. In this example, the player initiated shoulder flexion by activating deltoid muscles approximately 600–800 ms prior to ball impact (main recruitment started around 400 ms). Biceps brachii, as a major elbow flexor, followed at about 200 ms prior to ball contact. Triceps brachii as an elbow extensor co-contracted with the arm and forearm flexors dynamically stabilizing the forearm with respect to the shoulder. Wrist muscle activity mainly served to stabilize the racquet with respect to the hand.

To quantify how muscle activity in a particular muscle changed from the beginning of testing until reaching *near exhaustion*, we computed the ratio of IEMG at *near exhaustion* over IEMG at *baseline*. The median IEMG ratios for the 5 muscle groups ranged from 89 to 100% for the VDT racquet and 86 to 101% for the non-VDT racquet. Deltoid, as the most proximal muscle, showed no change in activity, while triceps, and the distal wrist extensor and flexor muscle groups exhibited reduced activity (Fig. 7). In general, the use of non-VDT racquet was associated with lower IEMG ratios compared to the VDT racquet. It needs to be recognized the

Table 2Mean peak acceleration of 10 hits at the baseline and near exhaustion states. Values in parentheses represent one standard deviation. Units are $g = 9.81 \text{ m/s}^2$.

Axis	Racquet				Hand				Forearm			
	Baseline		Near Exhaustion		Baseline		Near Exhaustion		Baseline		Near Exhaustion	
	non-VDT	VDT	non-VDT	VDT	non-VDT	VDT	non-VDT	VDT	non-VDT	VDT	non-VDT	VDT
X	87.03 (17.07)	72.93* (10.38)	82.23 (46.31)	75.97 ^a (43.69)	38.29 (14.21)	39.92 (8.76)	24.89 (7.57)	31.33 (11.78)	8.11 (1.86)	7.99 ^a (3.53)	7.49 (2.02)	8.00 (1.21)
Y	276.75 (49.94)	284.65 (36.70)	251.18 (35.99)	244.35 (26.29)	41.58 (17.99)	35.37 (11.69)	24.68 (10.85)	29.35 (8.26)	10.35 (3.62)	8.88 (3.51)	9.78 (3.66)	7.55 ^a (6.00)
Z	101.49 (13.23)	96.86 (12.43)	93.92 (11.58)	98.12 (15.54)	43.66 (16.54)	41.59 (11.22)	41.99 (24.09)	37.06 (18.59)	8.36 ^a (2.51)	7.65 (1.68)	6.91 ^a (7.91)	7.24 ^a (4.14)
Resultant	272.93 ^a (59.60)	290.75 (33.82)	261.99 (35.99)	260.06 (23.16)	61.88 (22.14)	55.09 (13.13)	41.53 ^a (37.24)	49.50 (19.44)	12.63 ^a (5.30)	11.49 ^a (4.61)	12.67 (8.34)	10.81 ^a (2.62)

Note. See Fig. 1B for orientation of the acceleration axes x, y, and z.

*significant difference after correcting for multiple comparison.

^a Median and interquartile range are reported for distributions significantly different from the normal distribution.

Table 3Mean ASE₁₀ at baseline and near exhaustion states. Values in parentheses represent one standard deviation. Units are ($g = 9.81 \text{ m/s}^2$).

Axis	Racquet				Hand				Forearm			
	Baseline		Near Exhaustion		Baseline		Near Exhaustion		Baseline		Near Exhaustion	
	non-VDT	VDT	non-VDT	VDT	non-VDT	VDT	non-VDT	VDT	non-VDT	VDT	non-VDT	VDT
X	60896 (24685)	42363* (13289)	40914 ^a (55866)	48046 ^a (33418)	23054 (12144)	25916 (11255)	12317 (5659)	19909 (11115)	1711 (588)	1769 (583)	1136 ^a (1160)	1622 (456)
Y	775575 (248876)	865212 (181252)	688790 (235733)	651280 (174882)	28374 (17426)	22211 (12458)	11939 (8900)	15417 (7230)	1620 ^a (1452)	1648 (969)	1424 ^a (2542)	1233 ^a (1959)
Z	123336 (44869)	96040 (32878)	104051 (28004)	90056 (29631)	22663 (15396)	23560 (12994)	23301 (19263)	13470a (17744)	1538 ^a (4544)	1512 (672)	1105 ^a (3698)	1382 (796)
Resultant	972774 (183387)	1032886 (279667)	802704 (350155)	878641 (292907)	79838 (47345)	62743 (50379)	49445 (31327)	56331 (27058)	4707 (5095)	4608 (1440)	4009 ^a (4285)	4369 ^a (4167)

*significant difference after correcting for multiple comparison.

^a Median and interquartile range are reported for distributions significantly different from the normal distribution.

data show large between-subject variability and differences in muscle activation between racquets are mostly not discernible.

As another marker of muscle fatigue, we determined the median power frequency during maximal voluntary isometric contraction (f_{MVIC}) for each muscle before the onset and after cessation of play. Based on the analysis of these f_{MVIC} ratios, we found no evidence of muscle fatigue for both racquet types for the wrist flexors ($M \pm SD$ VDT: $4.64\% \pm 7.99\%$, non-VDT: $4.46\% \pm 6.86\%$; effect size: $d = 0.02$). However, the use of the non-VDT racquet was associated with a decrease in f_{MVIC} at the wrist extensors, which was not observed for VDT racquet ($M \pm SD$ VDT: $14.8\% \pm 11.7\%$, non-VDT: $7.9\% \pm 15.6\%$; $p = 0.002$; effect size: $d = 1.65$). Analysis of the individual subject data revealed that 45% of players exhibited a sizable decrease in wrist extensor f_{MVIC} (range: 12% to -63%) when handling the non-VDT racquet, which they did not exhibit when using the VCT racquet (range: 3.5% to 29%). When compared to the VDT racquet, all but one player showed lower wrist extensor f_{MVIC} ratios for the non-VDT racquet (mean difference: 25.5%; range: 8.3% to -76.3%).

Analysis of grip force strength as a biomechanical marker of muscle fatigue did not reveal systematic effects of VDT on F_{grip} ($M \pm SD$ VDT: $F_{grip-baseline}$ 208.6 \pm 75.1 N; $F_{grip-near\ exhaustion}$ 197.6 \pm 77.8 N; non-VDT $F_{grip-baseline}$: 218.3 \pm 72.5 N; $F_{grip-near\ exhaustion}$ 203.5 \pm 84.7 N).

Measurements of tennis performance

Analysis of the radar-based ball speed data showed no significant differences in ball speed either between racquets or between the states across all the participants (see Fig. 8A). A second assessment concerned ball placement into the opponent's court for forehand stroke returns. Pooling the ball placement data for all participants at each state revealed that at near exhaustion players using the VDT racquet placed 25.0% of

their returns in the target area, while 17.6% of balls landed in the target area when they used the non-VDT racquet. This translates into a relative mean difference of 40% with respect to number of balls accurately placed when players were near perceived exhaustion. A third assessment concerned the total number of hits until exhaustion. On average, players hit about 11% more forehand strokes until they reached near exhaustion with VDT racquet compared to the non-VDT racquet (Forehands: effect size: $d = 0.33$; Fig. 8C). However, this difference between racquets was not statistically significant given the large between-subject variability (4 participants using non-VDT racquet and 2 subjects using VDT racquet reached near exhaustion in Block 2).

Discussion and implications

This study investigated the effect of VDT in a tennis racquet design that employed vibration damping composite materials. Specifically, we examined the effects of VDT on racquet vibration, on vibration transfer to the hand and forearm, and how potential differences in mechanical racquet behaviour relate to muscle fatigue and tennis performance. The field testing scenario was quasi-realistic in the sense that the arm motion of players were unconstrained and they were free to move on the court while either placing serves or returning balls in rapid order from a ball machine. The main results are summarized as follows: First, VDT substantially dampened racquet vibration. Resultant acceleration signal energy for the freely suspended VDT racquet was significantly lower (-74%) when compared to the non-VDT racquet. Second, when both racquets were handled by tennis players normalised resultant ASE₁₀ at the VDT racquet was still significantly lower (-40%) when compared to the non-VDT racquet. Third, there is initial evidence that VDT racquet use might prolong the onset of muscle fatigue. At near exhaustion the use of the VDT racquet was associated with lower levels muscle fatigue at the

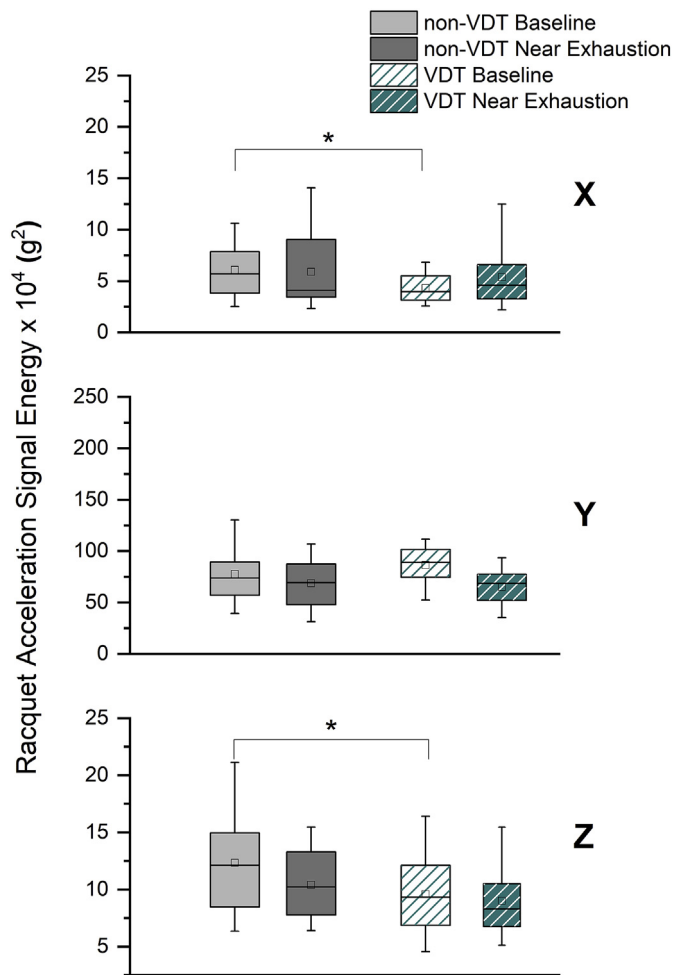


Fig. 4. Acceleration signal energy (ASE₁₀) during forehand strokes measured at the racquet shaft. The horizontal line inside the box indicates the group median. The square inside of box indicates the group mean. The box boundaries indicate the 25th and 75th percentiles, respectively. Whiskers indicate the 5th and 95th percentiles. **p* < 0.05.

wrist flexors and the forearm flexor and extensors. Fourth, there is inconclusive evidence that VDT racquets preserve tennis performance when fatigue sets in.

Vibration damping technology reduced racquet vibration and vibration transfer

Results of the present study show that the tested vibration dampening technology effectively reduced vibrations of the racquet frame when freely suspended or when handled by a player. When compared to a non-VDT racquet, the VDT racquet reduced vibration by approximately 74% during laboratory testing in free suspension. When tennis players actively used the racquet for forehand returns, normalised acceleration signal energy was reduced by approximately 40% during unfatigued play. Importantly, the dampening effect was maintained during fatigued play (34% reduction when compared to non-VDT; see Fig. 5).

A second aim of this study was to investigate the effect of VDT on the vibration transfer to the player's hand and arm. The peak accelerations measured at the hand in this study were comparable to previous work that reported mean peak acceleration of 26 g at the wrist in male expert players and 22 g in recreational male players.²⁵ Expectedly, vibration was markedly attenuated by the soft tissue of the hand and forearm. Peak resultant acceleration at the hand was approximately half the racquet acceleration and about 5% of racquet acceleration at the forearm. We

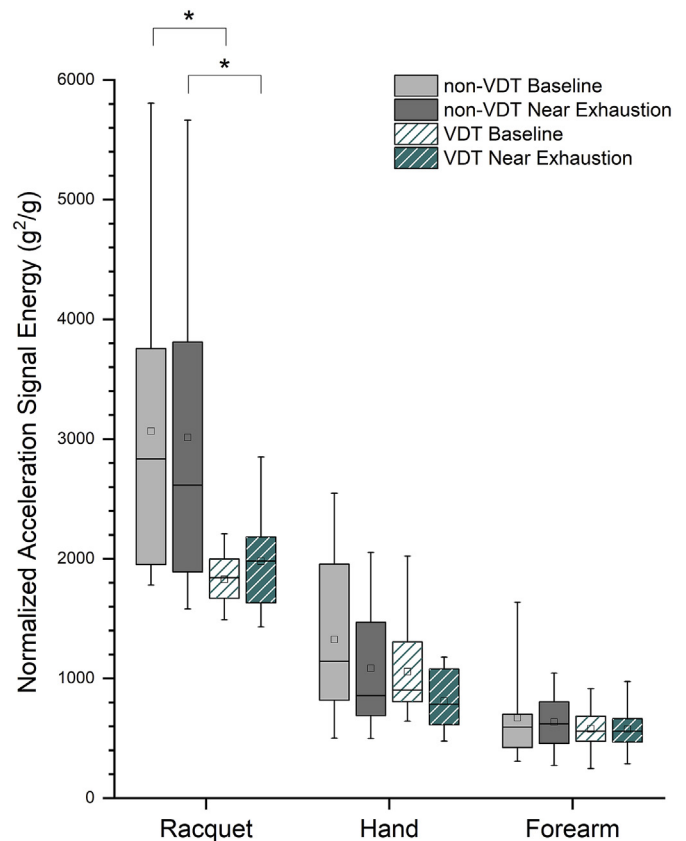


Fig. 5. Normalised ASE₁₀ at the racquet, hand and forearm during forehand strokes. The horizontal line inside the box indicates the group median. The square inside of box indicates the group mean. The box boundaries indicate the 25th and 75th percentiles, respectively. Whiskers indicate the 5th and 95th percentiles. **p* < 0.05.

obtained inconclusive evidence that VDT reduced vibration transfer to the hand. Normalised ASE₁₀ was 20–25% lower in the VDT racquet than the non-VDT racquet during unfatigued and fatigued play at the hand (see Fig. 5). However, while such reductions constituted a medium effect size (*d* = 0.52–0.67), these differences between racquets were not statistically significant given the high between-subject variability. A potential confound that likely affected the variability of vibration measurements at the hand was the grip force exerted by the player. Higher grip force is associated with higher vibration transfer to the arm.^{5,6,26} We here intentionally did not control for grip force in this study, because ordering players to exert fixed levels of force during field-testing would have constrained their behaviour and likely introduced other confounds. Thus, to answer the question about the magnitude of reduction in vibration transfer due to VDT conclusively, an experiment that controls for grip force would be necessary.

Effects of VDT on muscle activation during fatigued play

A third aim of the study was to examine the effects of VDT on patterns of muscle activation. If VDT reduces mechanical racquet vibration, then how would neuromuscular activity change in response to the altered mechanical behaviour of the racquet? Potential benefits of a VDT racquet should become most prominent during fatigued play. Specifically, those muscles stabilizing the wrist and possibly the more distal forearm should show less signs of fatigue. In broad terms, muscle fatigue is defined biomechanically as a decrease in maximal force or power output that muscles can produce.²⁷ It is known to be task dependent, meaning that there is no single cause of muscle fatigue and the dominant physiological fatigue mechanism is specific to the task.^{28,29} Expert tennis players

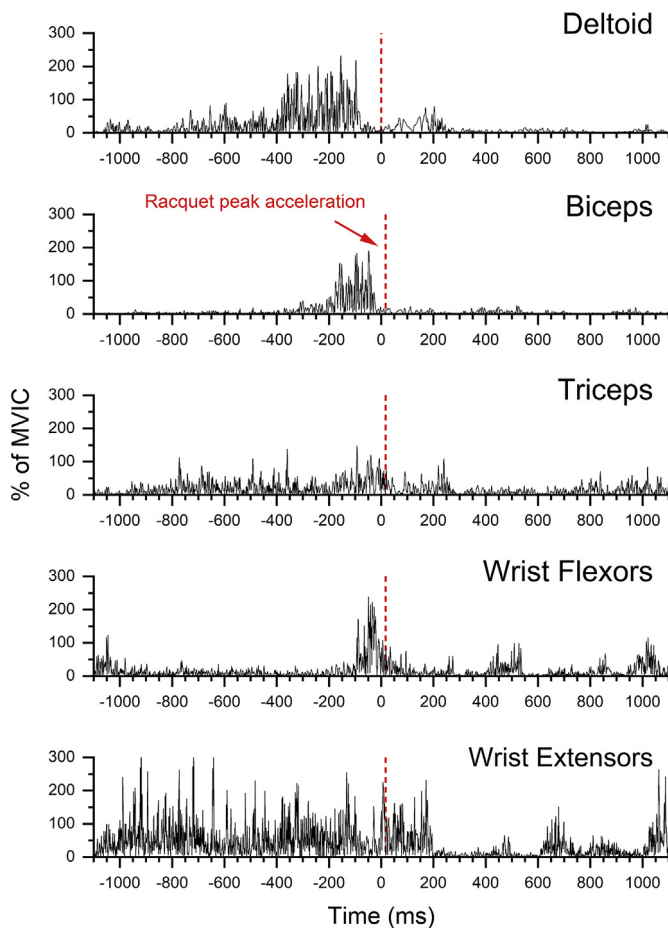


Fig. 6. Exemplar muscle activation pattern of a single forehand stroke from one participant using the VDT racquet at baseline. Time is aligned to the peak y-axis acceleration at the racquet to illustrate preparatory and post-impact EMG activity. MVIC = maximum voluntary isometric contraction.

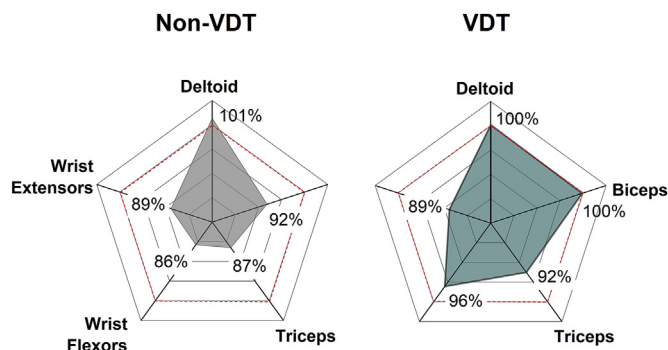


Fig. 7. Comparison of changes in muscle activation patterns between racquets. The radar plot shows the median IEMG ratio of each recorded muscle or muscle group. An IEMG ratio value of 100% indicates no change in muscle activation with respect to baseline values (see dashed red line pentagon). Players showed signs of fatigue using both racquets with IEMG values dropping below 1 especially for the wrist muscles. Proximal deltoid muscle showed no signs of fatigue for both racquets. Note the larger area of the VDT pentagon indicating that fatigue levels were lower for the wrist flexors, triceps and biceps muscle. * $p < 0.05$.

showed a reduced accuracy up to 69% when achieving the high-intensity fatigue criteria (>90% maximal heart rate).³⁰

To understand the effects of VDT on muscle activation at *near exhaustion*, the activity of five arm muscle groups were recorded using a wearable EMG. Previous research studying the electrophysiological

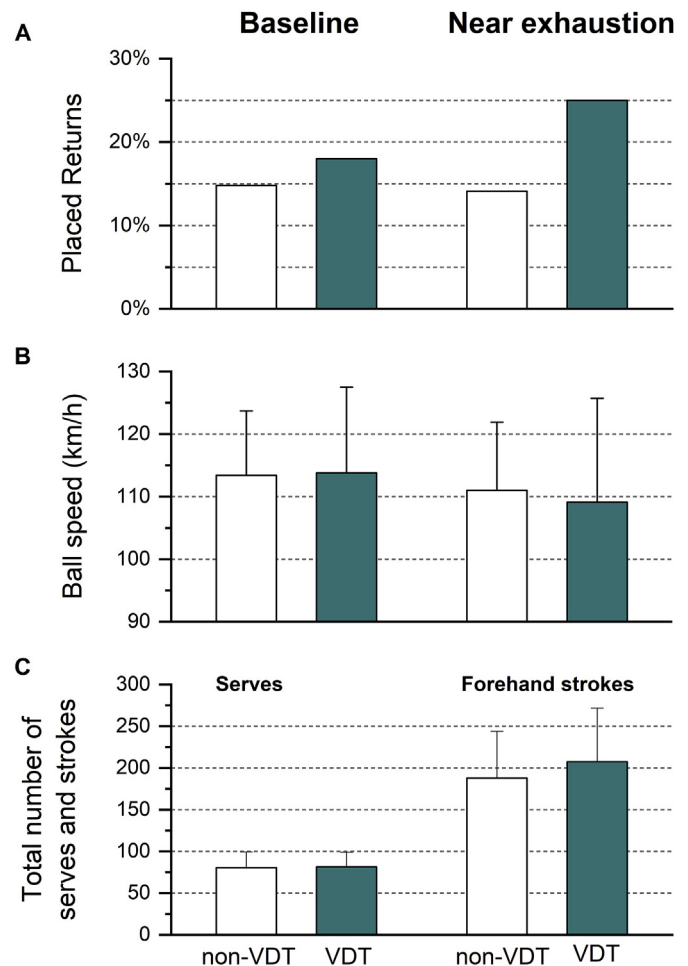


Fig. 8. Markers of tennis performance. (A) Spatial accuracy of return ball placement during forehand strokes for all participants with complete datasets ($n = 16$), indicated by the number of returns landed within the target area as a percentage of total number of hits. (B) Ball speed during serves for all participants. Error bars indicate standard deviation. (C) Total number of serves and forehand strokes hit by all players on average until exhaustion.

correlates of muscle fatigue measured EMG during maximum isometric contraction testing before and after exercise.²⁹ We here measured EMG activity during exercise by recording muscle activity associated with ball returns, and then computing normalised integrated EMG activity over the 10 strokes in each state. Our analysis primarily focused on a comparison between *baseline* and *near exhaustion* muscle activity for each racquet. Expectedly, we found that players showed signs of muscular fatigue for both racquets. Median reductions in IEMG of up to 14% with respect to baseline activity were observed at *near exhaustion*. The anterior deltoid, as the most proximal muscle, showed no change in activity, while triceps, and the distal wrist extensor and flexor muscle groups exhibited reduced activity at the *near exhaustion* state. That is, the more distal arm muscles moving the elbow and wrist fatigue first in prolonged tennis play. Overall, these results are consistent with previous work²⁹ showing that as tennis players fatigue, isometric muscle activity in the pectoralis major, the wrist flexors and extensors (flexor carpi radialis, extensor carpi radialis) was reduced.

Comparing the dynamic EMG activation patterns during play across racquets showed that the use of non-VDT racquet was associated with lower EMG activity in the biceps, triceps and wrist flexors at the *near exhaustion* state. However, given the large between-subject variability that can be expected during unconstrained multi-joint movement, the only the difference in IEMG ratio of the biceps brachii reached statistical significance (see Fig. 7). Given that the wrist flexors and extensors

control hand position during play, and given that effective VDT should reduce racquet vibration and transfer to the hand, it is sensible to expect that those same muscle groups shall benefit from VDT in terms of fatigue reduction. Thus, we analysed a second marker of muscle fatigue that was based on the EMG activity recorded during maximum voluntary contractions before and after field-testing. Analysis of the median power frequency (f_{MVIC}) of the wrist muscle EMG signals during these isometric contractions revealed that f_{MVIC} obtained after the cessation of tennis play had significantly decreased for wrist extensors when players used the non-VDT racquet when compared to the VDT racquet. A decrease in the median power frequency is a strong indicator of muscular fatigue.²¹ For the VDT-racquet, we actually found that players generally exhibited an increase in median power frequency at posttest, clearly indicating that the wrist extensors were not fatigued. Knowing that the functional role of the wrist extensors is to aid the proper positioning the racquet for the incoming ball during forehand strokes, preserved wrist extensor control or a delayed onset of fatigue would be beneficial for a tennis player.

In contrast, there is inconclusive evidence that VDT reduces fatigue at wrist flexors. Wrist flexors play an important role in tennis as they stabilize the wrist and racquet against ball impact in forehand strokes. At *near exhaustion*, our EMG analysis showed a 4% reduction of wrist flexor activity for the VDT racquet versus a 14% reduction of the non-VDT racquet. However, this difference was not significant because activity patterns were highly variable across players. In addition, analysis of signal power frequency during MVIC testing at the end of testing indicated no differential levels of wrist flexor fatigue between the two racquet types. In summary, this study provides initial evidence that VDT applied to tennis racquets may preserve arm muscle innervation patterns at late stages of the game or delay the onset of muscle fatigue. We firmly can state the biceps brachii and wrist extensors did not fatigue when players used the VDT racquet, while signs of muscle fatigue became evident when the same players used the non-VDT racquet.

Effects of VDT on tennis performance

A final aim of this study was to assess, whether VDT in tennis racquets is associated with a slower decline in tennis performance after prolonged play. It is evident that tennis performance in a long match is dependent on skill level and physical fitness. An analysis of serves at five-set matches at Wimbledon showed that top professional male tennis players are capable to maintain serve speed and accuracy between the first and the fifth set.³¹ Other studies documented that when players reduced ball landing accuracy during forehand strokes by 26% after 40 min,²⁹ while recreational players dropped their accuracy by 69% after 35 min.²⁸ In both studies, the fatigue test consisted of hitting returns against the ball machine. We here tested skilled, physically fit expert players who train under professional conditions and compete at the national level in the United States. At the time of testing, they were in season. Our analysis found no discernible difference of VDT in terms of ball speed during forehand returns. However, at *near exhaustion* ball accuracy was improved more when players used the VDT racquet. They placed 25% of their returns in the target area, while 17.6% of balls landed in the target area when they used the non-VDT racquet (see Fig. 8). This translates into a relative mean difference of 40% with respect to number of balls accurately placed when players were near exhaustion.

Limitations of the study

This study set out to examine the effect of VDT incorporated into the design of a tennis racquet frame design. We examined this VDT not under highly controlled laboratory conditions, but on the tennis court under quasi-realistic playing conditions. We allowed players to move freely on the court and did not impose constraints on how forceful they placed serves and returns. Consequently, factors like grip position, grip force, or racquet velocity and acceleration at ball impact that are known to influence racquet vibration^{6,32} were not fully controlled.

Another potential source of variability arose from removing and then re-attaching the accelerometers to the participants' skin for the two testing sessions.³³ Although we carefully monitored of accelerometer placement, we cannot guarantee that the anatomical positions between testing were identical. Despite these sources of variability, the accelerometer measures provided a useful information on the impact and potential benefits of VDT on the mechanical vibration behaviour of racquet when used by a tennis player on the court.

Electrophysiological signals from muscles are inherently variable within humans when recorded at different instances of time. They are also highly variable across humans, even if they perform the same highly practiced movement pattern such as a forehand stroke in tennis. An additional source of variability was due to our experimental approach of determining muscle fatigue. While the Borg scale of perceived exertion is widely established, it is no substitute for a physiological marker of muscle fatigue as it primarily quantifies cardiovascular exertion. Although we cannot guarantee that all players achieved the same level of physiological muscle fatigue, our EMG analysis did reveal the onset of physiological fatigue in biceps and wrist extensor muscles and did document the differential impact of VDT on muscle fatigue.

Conclusion

Vibration dampening technology applied to racquet frame design effectively reduces mechanical racquet vibration after ball impact. There is inconclusive evidence how vibration transfer to the arm is affected. While VDT in racquets reduces vibration transfer to the hand, the effect was highly variable likely due to differences in applied grip force. The study provided conclusive, initial evidence that VDT applied to tennis racquets can reduce or delay signs of muscular fatigue after prolonged play. Moreover, when players reached a fatigued state, the use of the VDT racquet was associated with improved ball control or accuracy. However, while VDT racquets may guard against early muscle fatigue, multiple other factors such as cognitive fatigue will influence tennis player performance at that stage.

Conflict of interest

All authors declare no financial or personal conflict of interest.

Submission statement

The data reported in this manuscript have not been published elsewhere and the manuscript is not under consideration for publication in another journal.

Each authors' contributions

Conceived the study design and analysis: IY, NE, JK.
 Collected the data: IY, SK, NE, RF, AM.
 Contributed to data analysis tools: SK, AM.
 Performed the analysis: IY, SK, NE, RF, AM.
 Wrote the manuscript: IY, NE, JK.

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