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The Impact of Aging and Hand Dominance on the Passive Wrist Stiffness of Squash Players: Pilot Study

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Abstract

Background: Passive joint stiffness can influence the risk of injury and the ability to participate in sports and activities of daily living. However, little is known about how passive joint stiffness changes over time with intensive repetitive exercise, particularly when performing unilateral activities using the dominant upper limb.

Objective: This study aimed to investigate the difference in passive wrist quasi-stiffness between the dominant and nondominant upper limb of competitive squash players, compare these results with a previous study on young unskilled subjects, and explore the impact of aging on wrist stiffness.

Methods: A total of 7 healthy, right-side dominant male competitive squash players were recruited and examined using the Massachusetts Institute of Technology Wrist-Robot. Subjects were aged between 24 and 72 years (mean 43.7, SD 16.57) and had a mean of 20.6 years of squash playing experience (range 10-53 years, SD 13.85). Torque and displacement data were processed and applied to 2 different estimation methods, the fitting ellipse and the multiple regression method, to obtain wrist stiffness magnitude and orientation.

Results: Young squash players (mean 30.75, SD 8.06 years) demonstrated a stiffer dominant wrist, with an average ratio of 1.51, compared with an average ratio of 1.18 in young unskilled subjects. The older squash players (mean 64.67, SD 6.35 years) revealed an average ratio of 0.86 (ie, the nondominant wrist was stiffer than the dominant wrist). There was a statistically significant difference between the magnitude of passive quasi-stiffness between the dominant and nondominant wrist of the young and older squash player groups (P=.004).

Conclusions: Findings from this pilot study are novel and contribute to our understanding of the likely long-term effect of highly intensive, unilateral sports on wrist quasi-stiffness and the aging process: adults who participate in repetitive sporting exercise may experience greater joint quasi-stiffness when they are younger than 45 years and more flexibility when they are older than 60 years.

KEYWORDS

wrist; exercise; aging

Introduction

Background

Joint stiffness is a biomechanical feature of human anatomy that is both essential and potentially detrimental to participation in sports, leisure activities such as music, and activities of daily living. Reduced joint stiffness may increase the risk of injury because of poor stabilization of joints and an inability to maintain joint postures [1,2]. Increased joint stiffness has been associated with reduced joint range of motion (ROM) and inflexibility, such as during the aging process [3,4], following surgical intervention [5], or because of abnormal muscle tone secondary to neurological injury or disease [6,7].which can cause both injury and functional limitations.

The term joint stiffness has various definitions depending on the discipline and nature of the research. In physical education, sports medicine, and allied health disciplines, joint stiffness is more commonly referred to as the flexibility, or ROM, of a joint or group of joints [8,9]. In the biomechanical literature, joint stiffness is referred to as the ratio of the change in joint torque to the change in joint angle [10]. Regardless of the definition of the term, joint stiffness is understood to be multidimensional, made up of (1) the elastic properties of noncontractile tissue (tendons, ligaments, and the joint capsule), (2) the elastic properties of intrinsic muscle cross-bridges, and (3) the reflex action of a muscle following change in length [11]. The different methods of assessment aim to distinguish between these components of joint stiffness, altering both the primary tissue structure under evaluation and the magnitude of joint stiffness reported. This study focuses on the measurement of passive joint quasi-stiffness, defined as the rate of change of resistance torque during a slow angular displacement of the joint, in the absence of muscle contraction [1,12].

Extensive research has been conducted on passive joint quasi-stiffness of the lower limb and the impact on gait [6,7], with less research focusing on the upper limb and the equally important impact on activities of daily living, leisure activities, and sports. Of the joints within the upper limb, the neuromuscular control of the wrist has been identified as being dominated by joint stiffness [13,14]. It is, therefore, of paramount importance that we develop our understanding of the properties and variables of passive wrist stiffness in different populations to better comprehend how stiffness impacts the planning and coordination of wrist movements by the neuromuscular system during functional and sporting activities.

Within the literature on wrist joint stiffness, there is large variability in the magnitude and orientation of passive joint quasi-stiffness, likely because of differences in study methodology (alignment and orientation of the starting position, ROM, number of degrees of freedom assessed, and the method of data analysis) as well as subject characteristics (including sex, hand dominance, participation in sporting and leisure activities, and age). Previous studies have investigated the impact of study methodology [15-17], sex [14-17], and hand dominance [17]. A recent study [17] demonstrated that there was increased passive wrist quasi-stiffness in the dominant upper limb compared with the nondominant upper limb of healthy young men and women. This finding suggests that there are biomechanical factors associated with increased use of the dominant upper limb that influence the passive stiffness of the wrist. To date, the impact of both participation in a highly unilateral sporting activity and aging on passive wrist quasi-stiffness has not been investigated, despite the vital function of the wrist in common sporting activities such as tennis, bowling, golf, badminton, and squash.

Objectives

Squash players were chosen as the target population for this study because of the highly repetitive, intensive, unilateral nature of the sport and for the vital role the wrist and forearm play in generating high racquet head speeds during the forehand and backhand stroke actions [18,19]. Research has demonstrated that exercise causes adaptations in the properties of muscle tissue such as muscle fiber size, type, and muscle cross-sectional area [20,21], which have been associated with changes in passive joint quasi-stiffness [1,22]. As increased mechanical stimulation of the wrist likely leads to adaptation in muscle tissue during competitive squash play, we hypothesize that (1) squash players will have a larger difference in wrist quasi-stiffness between the dominant (playing side) and nondominant upper limb, regardless of age, and (2) the orientation of wrist stiffness would be equivalent for all study participants. The purpose of this study was to further develop our understanding of joint stiffness by determining the impact of intensive unilateral exercise, in this case playing competitive squash, and the process of aging on wrist properties.

Methods

Recruitment

Volunteer competitive squash players were recruited with a study flyer posted on a local Web-based squash association newsletter. The inclusion criteria were as follows: (1) male, (2) aged 18 years or older, (3) no prior wrist surgery or injury, (4) English-speaking, and (5) a minimum of 5 years of playing experience. Only male subjects were recruited to reduce the risk of data variability, as previous work had demonstrated a difference in the magnitude and direction of wrist quasi-stiffness between the male and female sex [14-17]. Subjects were asked not to participate in any upper limb exercise in the 24 hours preceding their evaluation session to decrease the risk of reduced wrist ROM because of muscle swelling [11] and muscle thixotropic behavior [23] associated with eccentric wrist exercise. To ensure the study participants were competitive players, their squash skill level was recorded using the United States Squash Rating Algorithm (USSRA) [24]. The USSRA calculates a measure of each player's squash skill and ability using the data collected from all matches played in the last 45 months. Further details regarding the calculation of the algorithm can be found elsewhere [24].

Table 1. Subject demographics and age group allocation.

Group allocation	Young players				Older players		
	Subject 3	Subject 5	Subject 6	Subject 7	Subject 1	Subject 2	Subject 4
Age (years)[a]	31	42	26	24	61	72	61
Years of playing experience	20	25	12	10	37	53	20
Squash sessions/week (n)	5	2	4	4	3	3	4
US squash rating criteria by skill level	5.5	5	4.5	5.12	4.47	3	3.5
Hours post upper limb exercise	24	>48	>24	>48	24	24	>48

[a] Subject demographics were collected by interview before commencing the experiment.

A total of 7 healthy male competitive squash players aged between 24 and 72 years (mean 43.7, SD 16.57) volunteered to participate (Table 1). All 7 subjects identified as right hand-dominant for squash play, with 1 subject (subject 3 in Table 1) identifying as ambidextrous (left-hand dominant for activities of daily living, but right-hand dominant during squash play). The sample subject group had a mean of 20.6 years of squash playing experience (range 10-53 years, SD 13.85), a USRSL of 4.2 (range 3-5.5, SD 0.94—possible ranking ranges from 2 to 6, with 6 being the highest ranking), and reported playing between 2 and 5 times per week (median=4, mode=4). A total of 4 subjects were enrolled in the young squash group (mean age 30.75, SD 8.06 years), and 3 subjects were enrolled in the older squash group (mean age 64.67, SD 6.35 years). The Massachusetts Institute of Technology Committee on the Use of Humans as Experimental Subjects approved the study, with all volunteers providing written informed consent before participation.

Data from 7 right-hand dominant males (mean age 28.57, SD 12.11, range 19-55 years) reported in the study by Durand et al [17] (using the same experimental set-up) were used to compare wrist quasi-stiffness of unskilled subjects with the subjects participating in this trial who participate in regular, intensive, unilateral upper limb activity.

Evaluation Method: Massachusetts Institute of Technology Wrist-Robot

Wrist quasi-stiffness was evaluated using a 3 degree of freedom Wrist Robot (Figure 1, InMotion 3.0, Interactive Motion Technologies, Watertown, MA, USA), described elsewhere [25]. The robot forearm support positions the wrist joint so it aligns with the rotation axes of the robot. The Wrist Robot generates torques and simultaneously records the angular displacement produced into wrist flexion-extension (FE) and radial-ulnar deviation (RUD) [25]. A strap was used to lock forearm pronation-supination of the robot to eliminate confounding forearm movements during the trial. A gravity compensator was included in the robotic set-up to reduce the influence of gravity on the data collected. The gravity compensator was constant for each direction and equivalent to the sum of an average hand mass and the robot handle mass.

Figure 1. Massachusetts Institute of Technology Wrist-Robot and experimental forearm, wrist, and hand position (excluding finger strap).

Experimental Procedure

Subject demographics were collected in the form of an interview (Table 1). The experiment commenced randomly with the left or right upper limb (using the MATLAB randi X function, MathWorks, Natick, 2016, MA) [26]. The reference position for the upper limb was in keeping with the set-up of Durand et al [17] and Drake and Charles [14] to allow accurate analysis and comparison of study results; the elbow was flexed to 30°, the third metacarpal was aligned with the forearm, and the wrist was positioned in 0° wrist extension and 7° of ulnar deviation (UD). Although previous studies have used an almost neutral RUD wrist position (0° along wrist UD), this study and Durand et al [17] deliberately selected 7° of wrist UD as this initial wrist position was more comfortable, allowing subjects to remain in a passive muscle state and avoid unwanted muscle activity. The wrist and forearm position was verified with goniometry [27]. Hand grip remained relaxed and the forearm in a neutral position by wrapping a strap over the fingers, securing the hand to the Wrist Robot handle. Subjects were instructed to remain relaxed throughout the experiment, which was monitored by palpating the muscle groups responsible for wrist FE-RUD and checking the data collected between trials. The robot applied a torque of up to 1.95 Nm to reach a predefined target (from 0-20° along each direction defined through the 2D FE-RUD space) at a predefined speed (between 0.1 and 0.2 rad/s to inhibit muscle reflexes). Data were collected at a rate of 200 Hz. Each trial consisted of 36 movements (inbound and outbound movements) along 12 equally spaced directions through the space defined by FE-RUD. The movements started in pure wrist extension for the right upper limb (pure flexion for the left side) and proceeded counterclockwise, with each of the 12 targets reached once. This cycle was repeated 3 times during each trial to reduce the influence of any artifacts (reflex or small muscle contraction). A trial was conducted on the left and right side before repeating the sequence a second time. Out of the 2 trials for each subject, the trial with the least data noise (unwanted muscle activity) on the left and right wrist was used in the data analysis.

Statistical Analysis

Torque and displacement data were processed using a customized program in MATLAB 2016b [26]. Data collected before commencing each trial of 36 movements were removed, knowing the time to complete each movement, the number of movements, and the acquisition frequency. The processed data were then applied to 2 different estimation methods, the fitting ellipse [16] and the multiple regression (MR) method [28], to obtain wrist stiffness magnitude and orientation among the 4 parameters commonly used (listed below) to characterize a stiffness ellipse [16,28]

- Size: stiffness magnitude (ellipse surface [Nm/ rad]^2)
- Orientation: stiffness orientation (angle in degrees between radial deviation (RD) direction and ellipse major axis direction toward RD, counterclockwise angles are considered positive)
- Shape: the ratio of the major axis of the stiffness ellipse to the minor axis
- Equilibrium position: the offset of the ellipse center corresponding to the FE and RUD offset angles.

The fitting ellipse method (Figure 2) calculates the torque and angular displacement parallel and perpendicular to the direction of each of the 36 perturbations. Stiffness was then estimated (separately for outbound and inbound movements) by running a linear regression of the torque and the angle parallel to the perturbation direction. The mean stiffness values for the estimates of each of the outbound and inbound 36 perturbation directions were then used to fit a stiffness ellipse. Previous research indicates that the major weakness of the fitting ellipse approach is that it only considers the components of torque and angle parallel to the perturbation direction and does not include stiffness effects perpendicular to the perturbation direction. Of note, the fitting ellipse method allows for asymmetry of the elastic field with respect to the neutral position and is susceptible to data noise [17]. Although we fitted the stiffness values with a least square condition to keep consistent ellipse shapes, an excessive stiffness value along 1 direction will tend to stretch the ellipse and increase the size of the ellipse.

The MR method (Figure 2) determines the 4 elements of the stiffness matrix by multiple linear regression (using MATLAB's regress function [26]). Separate stiffness matrices were estimated for the inbound, outbound, and the composite of both movements. Each matrix was separated into the symmetric and asymmetric parts. Only the symmetric part of each stiffness matrix was displayed as a stiffness ellipse [28].

A 1-sample Kolmogorov-Smirnov test was used to confirm the normal distribution of the data. A 1-way analysis of variance was calculated to determine the statistical difference between the wrist quasi-stiffness of the left and the right arm in the young and older squash player groups and to compare the magnitude of the wrist quasi-stiffness and orientation of the 4 young squash players with the results of the 7 young right-handed dominant, unskilled male subjects [17]. The level of statistical significance for comparisons was set to $P<.05$. A Pearson r calculation was performed to determine the correlation between the magnitude of passive wrist quasi-stiffness in both the young and older squash groups and (1) age, (2) years of squash play, and (3) frequency of squash play.

Figure 2. (a) The fitting ellipse method, where variable τ represents torque, 'j' corresponds to 1 of the 12 directions considered through the FE-RUD plane, || means parallel to the wrist movement direction, and ⊥ means perpendicular to this direction. R_j is the rotation matrix for the jth direction, θ represents angular displacement, and 'K' represents quasi-stiffness [16]. (b) The MR method, where variable 'K' represents quasi-stiffness, 'FE' refers to flexion-extension, 'RUD' refers to radial-ulnar deviation wrist joint movement planes, τ represents torque, ∂ means partial derivative, θ represents angular displacement, 's' denotes the symmetric, 'a' represents the antisymmetric components of each stiffness matrix, and 'T' represents the transpose operation [28].

(a)

$$\begin{bmatrix} \tau_{j,\|} \\ \tau_{j,\perp} \end{bmatrix} = R_j \begin{bmatrix} \tau_{FE} \\ \tau_{RUD} \end{bmatrix}$$

$$\begin{bmatrix} \theta_{j,\|} \\ \theta_{j,\perp} \end{bmatrix} = R_j \begin{bmatrix} \theta_{FE} \\ \theta_{RUD} \end{bmatrix}$$

$$K_j = regress\left(\tau_{j,\|}, \theta_{j,\|}\right)$$

(b)

$$K = \begin{bmatrix} K_{FE,FE} & K_{FE,RUD} \\ K_{RUD,FE} & K_{RUD,RUD} \end{bmatrix} = \begin{bmatrix} \dfrac{\partial \tau_{FE}}{\partial \theta_{FE}} & \dfrac{\partial \tau_{FE}}{\partial \theta_{RUD}} \\ \dfrac{\partial \tau_{RUD}}{\partial \theta_{FE}} & \dfrac{\partial \tau_{RUD}}{\partial \theta_{RUD}} \end{bmatrix}$$

$$\begin{cases} [K_{FE,FE}, K_{FE,RUD}] = regress(\tau_{FE}, [\theta_{FE}, \theta_{RUD}]) \\ [K_{RUD,FE}, K_{RUD,RUD}] = regress(\tau_{RUD}, [\theta_{FE}, \theta_{RUD}]) \end{cases}$$

$$K_s = \frac{K + K^T}{2} \text{ and } K_a = \frac{K\text{-}K^T}{2},\ K = K_s + K_a$$

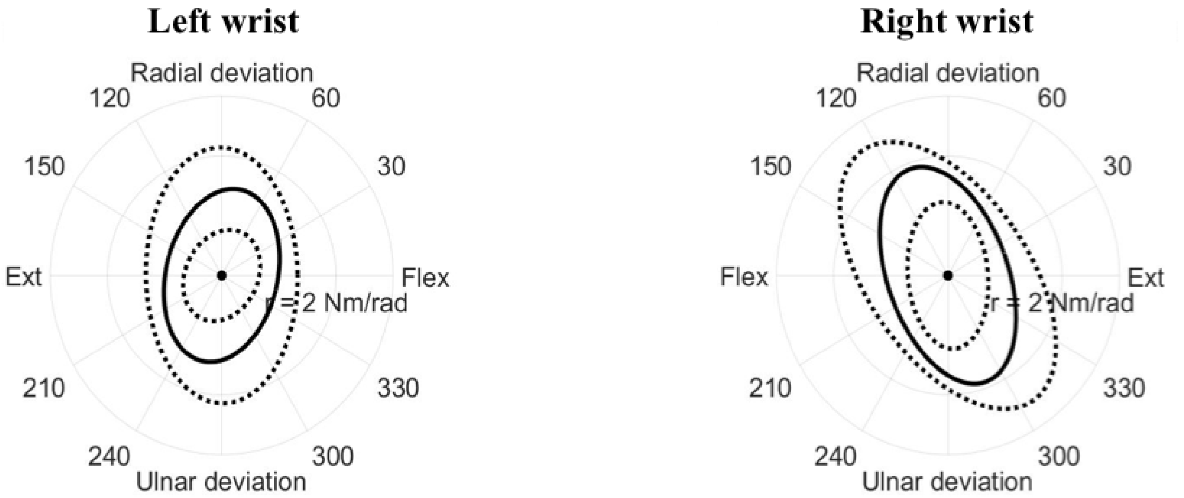
Results

Magnitude of Wrist Stiffness in Squash Players: Hand Dominance and Age Group Analysis

For the older adult group, the mean passive wrist stiffness magnitude of the left upper limb was 11.91 Nm/rad^2 (SD 1.26) and 9.99 Nm/rad^2 (SD 2.12) for the right upper limb. The ratio between right (dominant playing upper limb) and the left arm for the older adult group was 0.86. The older adult demonstrated a higher mean stiffness in the left (nondominant, nonplaying) upper limb (Figure 3). For the young adult group, the mean passive wrist stiffness magnitude of the left upper limb was 4.58 Nm/rad^2 (SD 1.39) and 6.75 Nm/rad^2 (SD 4.44) for the right upper limb. The ratio between right and left upper limb for the young squash group was 1.51. This playing group demonstrated a higher mean stiffness in the right (dominant playing) upper limb (Figure 4). There was a statistically significant difference between the magnitude of passive quasi-stiffness between the dominant and nondominant wrist of the young and older squash player groups (P=.004).

Figure 3. Mean passive quasi-stiffness ellipses (solid lines) and standard deviations (dotted lines) for the left and right wrist of the older adult squash player group (n=3).

Figure 4. Mean passive quasi-stiffness ellipses (solid lines) and standard deviations (dotted lines) for the left and right wrist of the young squash player group (n=4).



Magnitude of Wrist Stiffness in Young Adults: Unskilled and Squash Player Analysis

Results from the comparison of the 4 young squash payers (ratio right over left stiffness magnitude of 1.51) with the 7 young unskilled males (ratio right over left stiffness magnitude of 1.18) showed a stiffer dominant wrist for the squash players. There was no statistically significant difference between the young unskilled and the young squash player groups (*P*=.98).

Correlations: Magnitude of Wrist Stiffness and Subject Characteristics

The correlation between the passive wrist stiffness of all 7 players and subject characteristics revealed an interesting difference between the dominant and nondominant upper limb. There was a strong positive correlation between passive stiffness of the nondominant left wrist and age (R^2=0.87), whereas there was no clear correlation between passive wrist stiffness of the dominant right wrist and age (R^2=0.09) or years of squash play (R^2=0.01). When analyzing the correlation of the subject characteristics and the age subgroups, the young squash player group showed a strong positive correlation between passive wrist stiffness of the right wrist and the frequency of play (R^2=0.76). The older adult players demonstrated a strong negative correlation between passive wrist stiffness of the right wrist and the age of the player (R^2=0.88) and the number of years of playing experience (R^2=0.96).

Orientation of Wrist Stiffness: Unskilled and Squash Player Analysis

For the young unskilled group, the orientation of highest quasi-stiffness followed a “dart throwing” pattern, with a mean angle of 14.42° (SD 4.45) for the left wrist and a mean angle of –13.96° (SD 7.06) for the right [17]. For the young squash player group, the orientation of highest quasi-stiffness had a mean angle of 16.11° (SD 12.80) for the left wrist and a mean angle of –20.95° (SD 15.20) for the right. Both groups showed symmetric values for right and left wrists; however, a statistically significant difference was found between the unskilled and squash player groups (*P*<.001).

Discussion

Passive Wrist Quasi-Stiffness and Exercise

The magnitude of passive wrist quasi-stiffness of the young players confirmed the study hypotheses that competitive squash players demonstrate greater quasi-stiffness in the dominant playing upper limb compared with the nondominant upper limb. Although the ratio of dominant over nondominant wrist quasi-stiffness for young squash players compared with unskilled young subjects did not reach statistical significance, there was a trend favoring the squash player group. Studies investigating other sporting activities have shown that muscle strength, orientation of joint stiffness, and pattern of ROM between the playing and nonplaying upper limb do not consistently increase or decrease on the playing side. Klinge et al [29] studied the effect of strength training on flexibility and demonstrated that a 43% increase in isometric muscle strength resulted in a 25% increase in passive joint stiffness. Borsa et al [30] studied the difference in glenohumeral joint stiffness and ROM between the pitching and nonpitching upper limb in professional baseball players. Their results showed a difference in the ROM of the pitching and nonpitching upper limb but not a significant increase in passive stiffness on the pitching side. Indeed, the correlation between the measure of joint ROM and passive joint stiffness remains unclear. Some studies claim that joint ROM and passive joint stiffness (K) can be considered 2 components of the same phenomenon. Pando et al [15] demonstrated that the pattern of wrist stiffness was inversely related to the ROM ($K_{\text{Radial Deviation}} > K_{\text{Ulnar Deviation}} > K_{\text{Extension}} \sim K_{\text{Flexion}}$, whereas $ROM_{\text{Radial Deviation}} < ROM_{\text{Ulnar Deviation}} < ROM_{\text{Extension}} \sim ROM_{\text{Flexion}}$). However, in the study by Gleim and McHugh [31], an increase in ROM of a joint did not correspond with a decrease in passive stiffness of a joint or muscle. This study claimed that changes in ROM can be attributed to increased stretch tolerance without a change in stiffness magnitude [31].

There have been few studies, to the authors' knowledge, investigating the effect of exercise or sporting activities on passive wrist stiffness. Leger and Milner [11] investigated passive and active joint stiffness following wrist extensor muscle injury caused by a single session of intensive eccentric exercise. The study concluded that passive wrist stiffness (measured at a single neutral joint position) did not change following eccentric exercise-induced muscle injury. These findings suggest that this form of exercise does not cause mechanical changes to the noncontractile tissues in a neutral wrist position following a single session of such exercise. It is, therefore, likely that both differences in sporting activities as well as the biomechanics of joints will limit the comparison of our study results. Instead, an evaluation of the magnitude of quasi-stiffness in this study (of the young players), when compared with similar studies using unskilled subjects [15,17], reveals that passive wrist stiffness is slightly higher for competitive squash players. This trend in passive wrist stiffness is likely attributed to the greater cross-sectional area of the surrounding forearm muscles and tensile strength of the passive wrist structures (ligaments, tendons, and bone geometry), which are due to increased mechanical loading of the wrist during frequent, repetitive, and intensive squash play [32-35]. This conjecture is supported by the strong positive correlation (R^2=0.76) between the frequency of play and passive wrist stiffness in the young player group. The increased mechanical loading of the wrist associated with squash play may also explain the significant difference in the orientation of wrist quasi-stiffness between the unskilled and young squash playing groups. Nonetheless, as there is inconsistency in the orientation of wrist quasi-stiffness reported in the literature, it is possible that both differences in study subject's physical activities and study methodology contribute to the variance seen [14-17].

Influence of Aging and Exercise on Quasi-Stiffness

Although age-related increases in passive joint stiffness may seem clinically obvious, how exercise impacts passive joint stiffness in older adults has not been widely studied and results are inconsistent. Inconclusive results are likely because of variances in the joints evaluated, the study methodology, and the definition of flexibility and stiffness measurements. In research on flexibility, active older tennis players were shown to maintain shoulder flexibility on their playing side [36], whereas older soccer players were shown to have less flexibility in lumbar flexion and hip rotation than younger players [37]. Investigations into the effects of aging and immobility have shown that reduced physical mobility can be associated with increased passive stiffness. Lapier et al [38] and Gillette and Fell [39] found in animal studies that immobilization leads to increased intramuscular connective tissue and increased joint stiffness. In this study, the negative correlation between wrist stiffness on the dominant playing side and both the years of squash play (R^2=0.96) and age (R^2=0.88) in the older adult group strongly suggest that participating in high-intensity exercise could, in fact, slow or even prevent increases in joint stiffness during the aging process. This theory explains the higher stiffness magnitude on the nondominant (nonplaying) wrist in the older squash group and the significant difference in the magnitude of quasi-stiffness between the older and young squash players.

Changes to Muscle Fiber During Aging

The effect that squash play appears to have on the passive stiffness of the wrist with aging may partly be because of changes in the physiological properties of muscle fibers. The wrist flexor and extensor muscles are composed of approximately 50% type I and 50% type II muscle fibers in young adults aged 17 to 30 years [11,40]. Type II muscle fibers appear to be the most affected by aging, with reports of a 15 to 26% reduction in type IIa and IIb cross-sectional area and a preferential denervation of type II fibers between the age of 20 and 80 years [41]. The increasing proportion of smaller, slow-contracting type I muscle fibers with aging is thought to be an adaptive response to minimize fiber loss. The changes to type II muscle fibers and the increasing percentage of type I fibers are thought to be largely responsible for the reduced muscle mass, force generation of muscle tissue [41], and possibly the increased passive joint stiffness of older adults [42].

Type I muscle fibers have been reported to have greater passive stiffness, likely because of increased collagen concentration and cross-linking of collagen compared with type II muscle fibers [8,42]. Human and animal studies have demonstrated that an increase in type I muscle fibers leads to increased passive stiffness, whereas when physical exercise induces an increase in type II muscle fibers, there is a corresponding decrease in passive stiffness [8,42]. These observations might explain the pattern of passive wrist joint stiffness seen in the older squash playing group, where the left nonplaying wrist showed a higher passive stiffness (probably owing to an increased percentage of type I muscle fibers during the aging process) and the right dominant playing wrist demonstrating less passive stiffness (likely because of an exercise-induced relative increase or sparing of type II muscle fibers.)

Limitations

One must take this study with the appropriate caveats; several features of our study design limit the impact and generalizability of the results. Notably, the small sample size of this pilot trial significantly limits the power of the results. Other papers within this field of study have also reported small sample sizes ranging from 6 to 15 subjects [13-17]. The volunteer method of recruitment may have introduced self-selection bias, whereby the volunteer study subjects are not representative of the broader population that participate in squash or other unilateral upper limb sporting activities. Although the study recruited subjects with a wide age range, there were not enough subjects within each age group, and hence, for the most part, we only observed statistical trends favoring some of our conclusions. To reliably determine that there was a significant difference in wrist quasi-stiffness between the dominant (playing side) and nondominant upper limb of the older squash player group, a power analysis (GPower 3.1) indicates that (assuming an alpha value of .05, power of 0.80, and an effect size (f) of 0.32, calculated from the results of this pilot study) a total of 82 subjects would be required. Additional demographic data such as the duration of squash play, as well as the frequency of play per week, would better represent the subject's playing intensity and may enable more accurate characterization of the influence of playing intensity on passive joint quasi-stiffness. In addition, collecting data such as grip strength and electromyography would have provided further insight into the subject's muscle characteristics and muscle state during the trials to validate the measure of passive joint quasi-stiffness. Nevertheless, we believe our results provide additional information on a sparse landscape of limited literature on the impact of intensive unilateral exercise on passive joint stiffness. Indeed, the absence of comparative studies indicates that our study's findings are novel and potentially influential and that further research is required in this field.

Conclusions

This study provides a valuable initial insight into the possible effect that highly intensive, repetitive, unilateral sports may have over time on wrist quasi-stiffness and reducing the impact of the aging process. Further studies are required to investigate this relationship with a larger sample size and age group analysis. This field would also benefit from the study of passive wrist stiffness in young and older subjects who participate in intensive bilateral sporting activities such as upper limb weight or grip training to determine the magnitude and effect of changes in muscle fiber type across the lifespan. Our findings confirm that the evaluation of passive joint stiffness has relevance and far-reaching value in many fields, from sporting activities to the rehabilitation of the older adults, following surgical interventions, or those with neurological impairments.

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Conflicts of Interest

HIK is a co-inventor of several MIT-held patents for robotic therapy. He was the founder of Interactive Motion Technologies and Chairman of the Board (1998-2016). He successfully sold Interactive Motion Technologies to Bionik Inc. He founded 4Motion Robotics, Inc in 2017. TH is now employed by Bionik Inc, the company that purchased Interactive Motion Technologies.

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Abbreviations

FE: flexion-extension
MR: multiple regression
RD: radial deviation
ROM: range of motion
RUD: radial-ulnar deviation
UD: ulnar deviation
USSRA: United States Squash Rating Algorithm