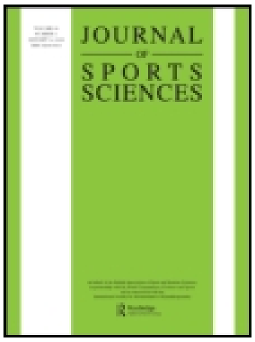

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Perceiving the affordance of string tension for power strokes in badminton: Expertise allows effective use of all string tensions

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Abstract

Affordances mean opportunities for action. These affordances are important for sports performance and relevant to the abilities developed by skilled athletes. In racquet sports such as badminton, different players prefer widely different string tension because it is believed to provide opportunities for effective strokes. The current study examined whether badminton players can perceive the affordance of string tension for power strokes and whether the perception of affordance itself changed as a function of skill level. The results showed that string tension constrained the striking performance of both novice and recreational players, but not of expert players. When perceptual capability was assessed, perceptual mode did not affect perception of the optimal string tension. Skilled players successfully perceived the affordance of string tension, but only experts were concerned about saving energy. Our findings demonstrated that perception of the affordance of string tension in badminton was determined by action abilities. Furthermore, experts could adjust the action to maintain a superior level of performance based on the perception of affordance.

Keywords: *affordances, constraints, motor expertise, badminton*

Introduction

A general belief held by racquet sports players is that playing performance is enhanced if the "right" string tension is chosen for their racquets. Often, we hear that elite tennis players prefer a particular string tension that has to be frequently checked during a match. In competitive badminton, it is often reported that experienced players prefer widely different string tension for their performance, and novice players request recommendations for ideal string tension when they first have their racquets strung. It remains unclear, however, what effect string tension has on performance by players at various skill levels.

Scientists have investigated the effect of string tension in tennis. Using the rigid clamping method, Elliott (1982) reported that a lower string tension resulted in a higher rebound velocity if the racquet was flexible. Bower and Sinclair (1999) found that rebound angle was influenced by string tension during an oblique impact. While a lower string tension produced greater rebound impulse (thus a greater velocity), the rebound angle was closer to normal. A change of rebound angle would directly affect stroke accuracy. Brody and Knudson (2000) modelled the dynamics of impact to determine the effect of string tension on stroke accuracy. According to their model, when string tension is lowered, the effect of a longer dwell time together with significant racquet rotation in recoil leads to a greater deviation between ball incident (the angle at which the ball impacts the racquet string bed) and rebound angle, thus making it difficult to control a shot. These results show that changes in string tension produce a speed-accuracy trade-off, such that reducing string tension helps to increase ball speed at the cost of decreasing accuracy.

The above conclusion is limited by the fact that it was based on testing only the dynamics of impact without including analysis or testing of human factors. In none of these studies did players interact with a strung racquet and ball. The question is whether the effects of string tension found in the laboratory would be seen in the field during play. Bower and Cross (2005) investigated this using a ball projection machine. Tennis players at competitive level were asked to return balls with three differently strung racquets. Rebound speed and accuracy were recorded. The results were in line with those reported in the previous laboratory

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studies, that is, low string tensions produced greater rebound speeds, but string tension seemed to affect ball placement and thus accuracy. In a subsequent study performed by the same researchers (Bower & Cross, 2008), elite tennis players were tested using the same procedure, but the results were conflicting. High string tension, instead of low string tension, produced significantly higher rebound speed, and ball placement did not appear to be related to string tension. The contradictory findings from these two studies suggest that the expertise of the players might play an important role in determining the effects of string tension on performance. Experts might be better able to adapt to the changing string tension to maintain superior performance. Bower and Cross (2003, 2008) also tested the tennis players' sensitivity to changes of string tension and reported that elite tennis players seemed to be insensitive to the changing string tensions. However, the limited ability demonstrated by elite tennis players in detecting changes of string tension might be attributed to the limited impact of string tension on their playing performance, although it remains unclear why string tension fails to affect this performance. The question that arises naturally is whether expert players can detect string tension and use this perception to adjust their stroke to yield consistent superior performance.

The study of affordances provides a new framework for investigation of string tension effects. Affordances are environmental properties of objects and events in relation to an animal's action capabilities relevant to performing specific tasks (Gibson, 1979/1986; Turvey, 1992). People are capable of perceiving affordances such as whether or not objects can be grasped (Newell, Scully, Tenenbaum, & Hardiman, 1989), reached (Mark et al., 1997), or climbed (Mark, 1987) given the scale of the observer and his or her relevant limbs (hands, arms and legs, respectively). In sport, the perception and use of affordances is critical to successful performance. Oudejans, Michaels, Bakker, and Dolne (1996) investigated the catch-ability of a flying ball and showed that movement, such as initiating approach to the future landing position, was required to perceive the affordance. Similarly, Hove, Riley and Shockley (2006) showed that hockey players were able to select the optimal hockey stick for power and precision tasks by wielding differently weighted sticks. Carello, Thuot, Anderson, and Turvey (1999) found that both novice and expert tennis players could judge the location of the "sweet spot" in a tennis racquet. As an essential property of racquets, string tension may provide opportunities for effective and successful play. In this case, however, the role of this property may depend on the level of skill of the player who is required to judge its affordance.

Perception of affordances entails a relation between the environmental properties and actor's action capabilities. As pointed out by Fajen, Riley, and Turvey (2008), perception of affordances could be dynamic due to changes occurring both in the environment and the actor. Actors can change in a number of ways (e.g. growth and development, injury, fatigue), but perhaps the most relevant to action capabilities in sport is the acquisition of effective skills. Such changes in an actor's action system will change the relation between environmental properties and the actor's action capabilities, which determines an affordance. An actor's perceptions have been found to adapt in the face of changes in these relations. For instance, Mark (1987) investigated the perception of maximum seat height when the sitters were asked to wear blocks to their feet, thus changing their relation to useable seat heights. It was found that the observers exhibited progressive adaption until judgments were again accurate, which occurred without experience of sitting while wearing the block. Similarly, Bingham, Schmidt, and Rosenblum (1989) had found that throwers could perceive and select objects of optimal weight for throwing to a maximum distance by hefting different hand held objects. However, Zhu and Bingham (2010) wondered whether this ability to perceive throwing affordance had to be learned through acquisition of long distance throwing skills. Unskilled throwers were unable to select optimal objects for throwing, but after a month of practice and acquisition of long distance throwing ability, they were able to do this task. The objects they selected at the end of the study were different from the ones with which they had trained, but still accurate. This study showed that the ability to perceive affordances is coupled with the ability to perform the relevant actions.

Using the framework of affordances, we now investigate the perception and use of string tension in badminton. Badminton is considered to be the world's fastest racquet sport. According to USA Badminton (Colorado Springs, Colorado, USA), the recorded speed of a shuttlecock immediately after impact could reach 206 miles per hour, that is, 1.6 times faster than the fastest ball in tennis. Although a relatively thinner string is used in badminton, allowing for more rebound speed during impact, a badminton court is significantly smaller in dimension than a tennis court. To keep shots within boundary while producing maximum speed, players select string tension to allow for accuracy as well as speed. This demand on string tension in badminton makes it an appropriate focus for study.

The current study is aimed to answer two research questions. First, does the optimal string tension exist for power strokes produced by players at different levels of expertise? It was hypothesised that different string tensions would result in different shuttlecock speeds after impact, and an optimal string tension should produce the greatest shuttlecock speed after impact. However, the expertise of the player was expected to affect how different string tensions were used. Hence, different string tensions might be found to be optimal depending on the player's level of expertise. Second, could players at different levels of expertise perceive the affordance of string tension for power strokes? It was hypothesised that the affordance would be better perceived by players with greater expertise, assuming that this would be part of their expertise (the perceptual expertise). However, is there a sensory mode that is optimal for perceiving this affordance? Badminton players judge string tension in various ways: by pressing the string bed directly, by listening to the sound resulting from hitting the string bed with heel of the hand, or by watching a shuttlecock bouncing off a racquet, and finally, by simply hitting several shots. According to Shaw and Bransford (1977), action-dependent properties should be specified equally well in optic, acoustic and haptic information. Hence, affordances should be perceived equally well using different sensory modalities. Warren, Kim, and Husney (1987) showed that the elasticity of a ball used for a bounce pass could be perceived equally well using visual and auditory information. Similarly, Fitzpatrick, Carello, Schmidt, and Corey (1994) showed that whether a slanted surface would support upright stance could be perceived both visually and haptically. Both studies implied that the affordance of string tension would be equally well perceived in different perceptual modes.

Methods

Participants

Twelve adult participants were recruited on the campus of the University of Wyoming (UW). They were selected to represent three skill levels in playing badminton: expert, recreational and novice. To be considered as expert players, participants were required to have played badminton actively and competitively within the last 5 years, and accumulated approximately 10,000 hours of deliberate practice in their lifetime (Ericsson, Krampe, & Tesch-Römer, 1993). To be considered as recreational players, participants were required to have played badminton or other racquet sports occasionally, but only for fun. Novice players may have played in a PE class before, but not have played otherwise on any occasion. All participants were interviewed about their previous experience of playing badminton to determine their level of skill. Four expert players (3 male and 1 female) and four recreational players (3 male and 1 female) were recruited from the UW Badminton Club. Four novice players (1 male and 3 female) were recruited from the regular student population. Participants were right-handed, aged between 20 years and 40 years, and free of any motor or sensory deficit. Informed consent was obtained as governed by the Institutional Review Board (IRB) at UW.

Apparatus

Using a stringing machine (Eagnas Combo 910, Gardena, CA), eight badminton racquets of the same model (Yonex Nanospeed 9000, Torrance, CA) were strung with the same type of string (Yonex BG 65) to achieve tensions of 16 lb, 18 lb, 20 lb, 22 lb, 24 lb, 26 lb, 28 lb, and 30 lb. The pulling tension for the main string was set at the target tension level, and that for the cross string was increased by 2 lb.

Since the resulting string tension typically requires time to settle after stringing, all strung racquets were measured and monitored for change of tension after the stringing. The actual string tension on each racquet was determined by measuring the vibration frequency of the strings (Cross & Bower, 2001; Röttig, 2010). The experimenter swung the racquet rapidly to hit the heel of his hand with the string bed. The resulting sound of impact was recorded directly onto a computer through a microphone set right next to the collision point. The fundamental frequency was determined using audio analysis software (*Audacity*). This frequency was then used in the following the equation to determine the actual string tension:

$$S = 8.82\,A\mu\frac{(0.988f)^2}{9.81\times 10^7} \quad (1)$$

where

A = area of the racquet head (to wincm^2)
μ = mass-density of the strings (densitg $\cdot$ m^{-1})
f = fundamental frequency of the strings in Hz
S = string tension in lbs.

It was found that string tensions on each racquet dropped significantly after stringing by about 6 lb, but these changes stopped after a month, similar to the findings of Cross and Bower (2001). The measured tensions after a month were compared to the intended tensions, and a significant correlation was found (F (1, 7) = 1688.7, P < 0.001, R^2 = 0.99), showing that the tension intervals were preserved despite the significant drop in the average tension.

Once the string tensions had stabilised, the corresponding impact sounds were saved and edited as auditory stimuli for later judgment tests. Eight sound tracks were saved for the eight tension levels, respectively. Each sound track was then edited to be five repetitions of the same impact sound evenly spaced in five seconds.

The string tensions were also recorded visually. Each racquet was fixed on a stringing machine with its string bed facing upwards. A small reflective ball (2 inch in diameter) was projected vertically from above the string bed from the same height at the same angle using a commercially available ball gun (Nerf Atom Balster). The motion of the ball before and after impact was recorded at 250 frames per second using a high speed camera (SportsCam 500 by Fastec Imaging, San Diego, CA) that was oriented perpendicular to the direction of motion. Eight video clips were made for the eight tensions, respectively. Each clip was then edited to be five seconds long and only contain the visual display of the bouncing ball event played at a rate of 30 frames per second.

The same fast speed camera (SportsCam) was used to record power strokes performed by participants using the various strung racquets. The camera was set on a tripod perpendicular to the primary plane of motion at a distance of five metres. The distance allowed maximum spatial resolution of the entire range of motion. Compatible software (MaxTRAQ 2D) was used to control the camera and record the motions at 250 frames per second with a shutter speed of 1/2500 second. A black curtain was behind the participant who was illuminated by two studio lights (Q60SG/1200-Watt by Smith Victor, Bartlett, IL). Using additional software (MaxMATE), two-dimensional (2-D) motion analysis was performed to recover speed and direction of motion of the shuttlecock after impact using a third order low-pass filter with a cut-off frequency of 15 Hz (Winter, 1990; Yu, 1988).

Procedure

First, the power stroke was described to participants as the stroke that will result in the greatest speed of the shuttlecock after impact. Then, participants were informed that the task was to determine the difference between string tensions on racquets, and select the tension that would allow for the most powerful stroke. They were encouraged to judge based on their own intuitive feeling without any subjective reasoning. Participants were subject to a perceptual judgment test first, in which they were asked to judge optimal string tension in each of three perceptual modes, and then the performance test in which they were asked to perform power strokes using racquets with the various string tensions. After the performance test, participants were asked to judge the optimal string tension again.

Pre-performance judgments. The eight string tensions were presented to participants in visual, auditory and haptic modes. The order of the perceptual modes was randomised. In the visual mode, participants watched eight silent video clips of a ball bounced off the respective string beds. In the auditory mode, participants heard eight sound tracks of the string beds being hit by the experimenter's hand. In the haptic mode, participants pressed the string bed of each racquet using their fingers with eyes closed and ears plugged. In each condition, tensions were initially presented either in an increasing or decreasing order. These orders were counterbalanced across participants. Participants were allowed then to compare different string tensions as many times as they wanted to select the best three string tensions in order, namely, the first, second and third preferred tensions.

Performance test. Perceptual judgments were followed by performance tests. Participants were encouraged to warm up their shoulders and arms before testing. Then, they were asked to swing a racquet three times at maximum speed. Next, participants were asked to perform power strokes using racquets strung with the different tensions. In typical game play, players are required to strike a flying shuttlecock during movement, however, the ability to locate and move underneath the shuttlecock to prepare for striking may confound the ability to use different string tensions to produce power strokes. Hence, we modified the striking condition by asking players to strike a static suspended shuttlecock above their head. A feather shuttlecock was hung from the ceiling through a nylon fishing line that had one end fixed to the ceiling and the other end folded to hook the skirt of the shuttlecock. The shuttlecock was suspended obliquely with its cork head going to be hit by the racquet first. Participants were asked to hold the racquet as comfortably as they would, and fully extend their arm upward so that they could reach high above their head with the racquet. Then, the suspended shuttlecock was adjusted to the participant's preferred striking height at which the string bed would make full contact with the shuttlecock during impact. Participants swung each racquet with maximum power to strike the shuttlecock so that it would detach from the fishing line, launch and land in the matted area on the front wall, which was located approximately 3 m away from where the shuttlecock was suspended. They were asked to do this three times using each racquet, yielding a total of 24 trials. All participants succeeded in striking the shuttlecock to hit the matted area. To prevent fatigue, a two minute break was provided between trials. String tensions were tested either in an increasing or decreasing order of tension, counterbalanced across participants, but the order was different from that in the perceptual judgment test. All trials were recorded using the high speed camera at a speed of 250 frames per second.

Post-performance judgments. Immediately after the performance test, participants were asked to judge preferred string tension again (selecting their top three choices again in order). They were told that their judgment should be based on their immediate feeling about each tension during and after producing power strokes. Participants' preferred tensions were recorded to compare with those judged previously.

Results

Effect of string tension on striking performance

The effect of string tension on striking performance was examined as a function of expertise. As shown in Figure 1, the mean maximum speeds varied with the string tension, but in different ways for different skill levels: they decreased for novice players, increased for recreational players, but remained steady for expert players, indicating that the effect of string tension on power strokes depended on the player's level of expertise. Speeds also varied as would be expected with expertise: they were greatest for experts, and least for novice players.

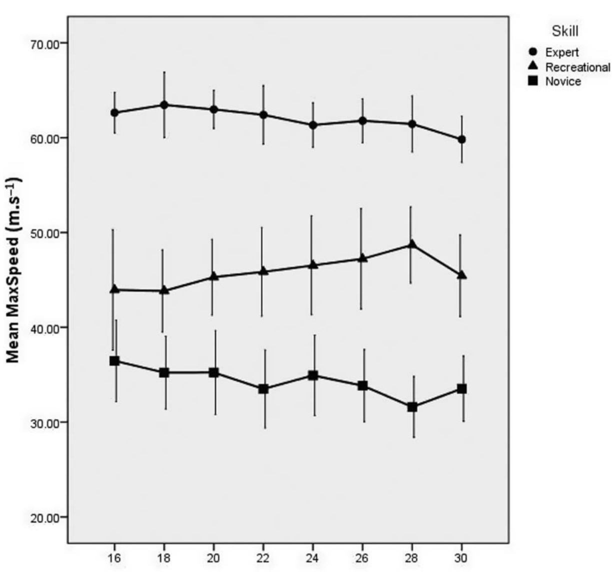

Figure 1. Mean maximum shuttlecock speed after impact as a function of string tension and skill level. Novice players (filled squares), recreational players (filled triangles), and expert players (filled circles). Error bars are standard errors.

A 3-way (skill by tension by trial) mixed design analysis of variance (ANOVA) yielded a main effect for skill (F (2, 9) = 21.45, $P < 0.001$, $\eta^2 = 0.83$). A Tukey post-hoc test showed that expert players generated a significantly higher ($P < 0.05$) maximum speed ($M = 62.0 \pm 4.5$ m $\cdot$ s^{-1}) than recreational players ($M = 45.8 \pm 8.2$ m $\cdot$ s^{-1}), or novice players ($M = 34.3 \pm 6.7$ m $\cdot$ s^{-1}). Because a significant interaction was also found between skill and tension (F (14, 63) = 2.90, $P < 0.01$, $\eta^2 = 0.80$), a simple main effect analysis was performed to determine the effect of tension within each skill level. Tension was significant for novice (F (7, 189) = 2.12, $P < 0.05$, $\eta^2 = 0.07$) and recreational players (F (7, 189) = 2.55, $P < 0.05$, $\eta^2 = 0.09$), but not for expert players (F (7, 189) = 1.26, $P > 0.1$). A Tukey-B post-hoc test was followed to find out the tension corresponding to the speed that was significantly higher than others, namely, the optimal tension. Among the mean speeds produced by novice or recreational players using all tensions, a peak mean speed can be identified. This peak mean speed was compared to other speeds until the significant difference was found. It was revealed that tensions of 16, 18, and 20 lbs corresponded to a speed significantly higher than those produced by other tensions for novice players, and tensions of 24, 26 and 28 lbs demonstrated the same for recreational players ($P < 0.05$). Thus, tensions as low as 16 lb were optimal for novice players, while tensions as high as 28 lb were optimal for recreational players, and expert players were able to produce equally fast strokes using all string tensions. A significant interaction between skill, tension and trial was also found (F (28, 126) = 1.60, $P < 0.05$, $\eta^2 = 0.26$). The simple main effect analysis was performed to evaluate the trial effect within each skill level, and the results indicated that a trial effect was significant only for recreational players (F (2, 144) = 17.11, $P < 0.001$, $\eta^2 = 0.19$), because they generated significantly lower speeds in their third round, suggesting that they might get fatigued in performing the final trial of the power stroke.

Perceptual judgment of the optimal string tension

Given the performance results showing optimal string tensions for recreational and novice players, but not for experts, the next question was whether those players would judge the respective tensions as optimal when the string tensions were presented to them in different sensory modes? To provide better resolution along this continuous dimension given the discrete choices, the mean preferred tension was calculated in each condition by multiplying the preferred tension by 0.5, the second preferred by 0.33, and the third by 0.17, and

Table I. Coefficient of variation (CV) of judged tensions preferred for power stroke.

Judgment Type	Expert	Recreational	Novice	Mean
Audio	0.05	0.06	0.11	0.07
Video	0.06	0.16	0.06	0.09
Haptic	0.13	0.10	0.16	0.13*
After-Hitting	0.16	0.07	0.09	0.11
Mean	0.11	0.09	0.14*	

Note: Asterisk represents the highest mean CV.

then summing them up. These calculated mean preferred tensions were then used as a dependent measure to examine effects of judgment type and motor expertise on judging the best tension for the power stroke.

A 2-way (skill by judgment type) mixed design ANOVA showed a significant effect for skill (F (2, 9) = 11.81, $P < 0.01$, $\eta^2 = 0.72$). As revealed by a post-hoc Tukey test, novice players selected a significantly lower ($P < 0.05$) tension (M = 22.5 ± 3.2 lb) than expert (M = 25.3 ± 2.8 lb) and recreational (M = 26.5 ± 2.6 lb) players, with no difference between the last two. These judgments were fairly reasonable for the novice and recreational players, but not for the experts, because the experts failed to exhibit an optimal string tension in their performance data, but nevertheless, they appeared to exhibit preferences for a higher string tension.

There was no main effect of judgment type (F (3, 27) = 0.27, $P > 0.5$), indicating that the same tensions were selected before performing the power strokes regardless of the perceptual mode (vision, audition, or haptic), as well as after players had tried striking with all of the tensions. Coefficients of variation (CV) were used to assess the variability of these judgments. As seen in Table I, novice players were more variable than skilled players in selecting an optimal tension, and judgments using the haptic mode were more variable than using other modes. This latter result implied that pressing on the string bed to judge the optimal tension was challenging for all players. Furthermore, as shown in Table I, there were some variations among players of different skill levels. The experts were most variable in judgments made after performing power strokes. This result indicated that their preference for higher tension became less reliable after they had actually used string tensions to hit shuttlecocks.

Perceiving the affordance of string tension

Two more analyses were performed to better determine whether the affordance of string tension was perceived accurately. First, participants' performance data was weighted by their judgment data as follows. For each participant, the mean maximum speeds of the shuttlecock after impact can be found for each string tension. These mean maximum speeds could be weighted by the participant's choices, that is, the speed corresponding to the most preferred tension was multiplied by 0.5, that corresponding to the second preferred tension by 0.33, and that to the third by 0.17 before they were summed to yield a weighted average speed. For those speeds corresponding to the discarded tensions, an average speed was computed by excluding the highest and the lowest scores to avoid possible ceiling and floor effects. Thus, two sets of mean speed scores were created: one corresponded to the selected tensions, and the other to the discarded tensions. An ANOVA was performed to examine choice and its potential interaction with skill level and judgment type. If we found that the speed corresponding to the selected tensions was higher than that corresponding to the discarded tensions, this would suggest that players were able to perceive the affordance of string tension. We found that the weighted mean maximum speeds were consistently higher than those for the discarded tensions only for recreational players. A 3-way (skill by judgment type by choice) mixed-design ANOVA showed a significant effect for skill (F (2, 9) = 21.91, $P < 0.001$, $\eta^2 = 0.83$, the same as found in analysis of performance data), and a marginal effect for the skill by choice interaction (F (2, 9) = 4.15, $P = 0.05$, $\eta^2 = 0.48$). Because we already found that higher speeds corresponded to higher skill level, and that the type of judgment did not affect selection of the optimal tension, post-hoc tests were performed only to investigate the skill by choice interaction. As revealed by simple main effect analysis, the choice effect was only significant for recreational players (F (1, 36) = 7.91, $P < 0.01$, $\eta^2 = 0.18$), suggesting that only recreational players were accurate in selecting the optimal tension for producing a power stroke.

To confirm this finding, another analysis was performed. This analysis was used previously by Zhu and Bingham (2008, 2010). For each participant, all tensions were weighted by a participant's mean preferred tension (actual tension/mean preferred tension), and all speeds were weighted by the peak

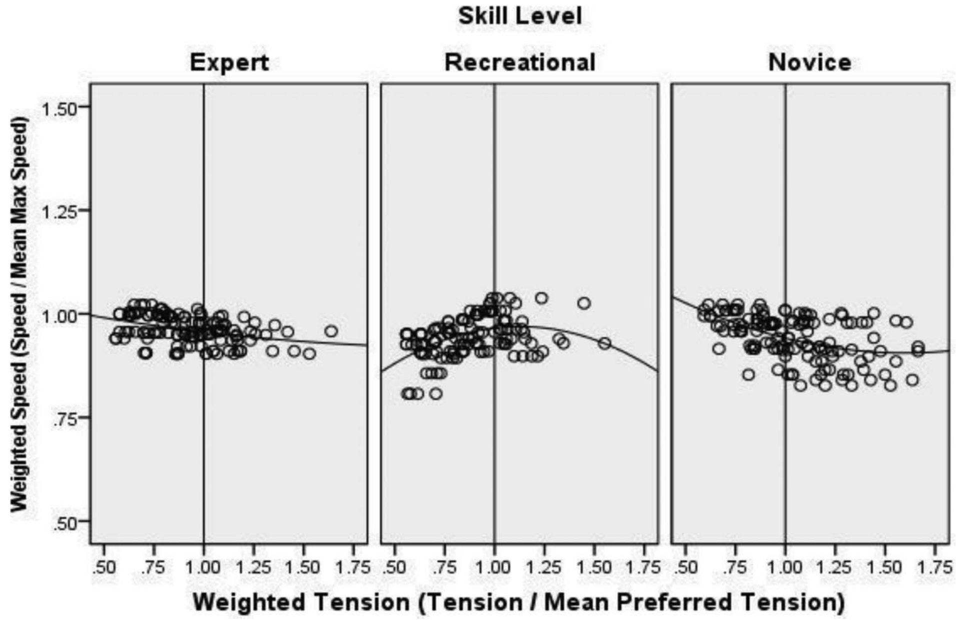

Figure 2. Quadratic regression of weighted tension on weighted speed separated by skill level. The vertical line refers to the condition when actual tension is equal to the mean preferred tension. If this line intercepts with the peak of the quadratic regression curve, which also corresponds to a value close to 1 on the Y axis, the accurate perception of tension affordance can be determined. However, this is only seen at recreational level.

mean maximum speed that was produced by the participant (actual speed/peak mean maximum speed). Then, the weighted speeds were plotted against the weighted tensions. If judgments of the affordance were correct, then the plot should exhibit a peak at the value of 1 on the axis of weighted tension (that is, where actual tension = mean preferred tension) and this peak should exhibit a value of 1 on the axis of weighted speed (that is, actual speed = peak mean maximum speed). This expectation could be evaluated by fitting a quadratic function to the combined data for players at each skill level. However, given the pattern for speed data exhibited in Figure 1, this analysis was expected to work only for the recreational players. As seen in Figure 2, for novice players, speeds peaked at the lowest level of string tension. For expert players, speeds exhibited no significant variation across different string tensions. Thus, good quadratic fits could not be expected in either case. The analysis only worked for recreational players. The regression analysis only yielded a significant ($P < 0.05$ or better) quadratic term for the recreational players ($R^2 = 0.21$, F (2, 127) = 16.56, $P < 0.001$, $Y = -0.23X^2 + 0.51X + 0.68$). The X can be solved by taking the derivative of this function and then setting the derivative as 0: $X = 1.11$. Thus, the maximum occurred close to 1 on the weighted tension axis. The function evaluated at this value for X was $Y = 0.96$, suggesting that the selected tension did yield the maximum speed.

Discussion

Anecdotally, string tension is believed to affect playing performance in racquet sports. Although the string tension effect has been investigated in tennis, little attention has been paid to motor expertise in determining the effect. The current study investigated the string tension effect in badminton as a function of different levels of expertise within the framework of affordances.

Our results and analyses revealed that recreational players were sensitive to the affordance of string tension. They selected a tension (≈ 26 lbs) that yielded a maximally effective power stroke for them, that is, a stroke that yielded the peak maximum speed. Novice players selected a tension (≈ 22 lbs) that was greater than the one that allowed them to generate the greatest maximum speed (≈ 16 lbs), although they did select a lower tension than did either recreational or expert players. Furthermore, novice players exhibited greater variability in their choices as might be expected given their level of skill. Finally, expert players reliably selected a higher tension (≈ 25 lbs) close to that preferred by recreational players, despite the fact that this tension failed to be the only one to yield the best performance. The experts generated equivalent maximum speeds using all string tensions. These speeds were greater than those produced by non-expert players as expected. Thus, according to these analyses, it seemed, rather paradoxically, that expert players were not expert in perceiving the affordances of string tensions. Is that true? To answer this question, we need to find out why expert players prefer higher string tension even though they were able to produce equally effective power strokes with all string tensions?

To begin with, we must first consider the effect of string tension on the dynamics of the shuttlecock after impact. In our method for displaying visual information about string tension, a reflective marker ball was dropped onto each set of strings from the same height so observers could see the resulting bounce height. This was similar to the method in Warren et al. (1987) who investigated perception of elasticity. The resulting bounce height increased with decreasing string tension because the restitution coefficient (V_{out}/V_{in}) is higher for lower string tensions (as reported by Elliott, 1982). This tension effect was directly evident in novice striking performance, where we noticed that the lower the tension, the faster the shuttlecock after impact. The implication is that variations in novice performance were purely determined by the elasticity of string tension.

In producing a power stroke, novice players merely used elbow flexion and extension with little follow through after striking. Skilled players performed strokes quite differently than less skilled players. Both recreational and expert players used a full body motion starting with a side stance, then swinging the racquet in a series of movements at major joints starting with the ankle and knee, and proceeding up to wrist and finger joints proximal to the racquet. These motions were similar to those exhibited in long distance over-arm throwing which entail a well-timed sequence of movements along these adjacent joints (Jöris, van Muyen, van Ingen Schenau, & Kemper, 1985; Zhu, Dapena, & Bingham, 2009). This timing is acquired through the extensive practice that eventually yields expert performance. Recreational players were able to increase the impulse (or total force of impact) in their power strokes by swinging the racquet faster. This also shortened the duration of contact between racquet and shuttlecock so that maximum energy was transferred to the shuttlecock. This transfer was facilitated, in turn, by a stiffer string bed. Thus, higher string tension yielded better performance for recreational players.

Expert players were also able to produce faster racquet speeds as were the recreational players, but obviously, they were doing something more to enable them to maintain the resulting high shuttlecock speeds despite variations in string tensions. Presumably, expert players were able to use wrist and finger flexion to increase speed at the racquet head even more to compensate for the loss of energy when using lower string tensions. Although the time allowed for the string bed to be stretched is minimal in their fast swings, expert players must take advantage of the longer dwell time provided by lower string tension (Brody & Knudson, 2000) to swing the racquet with additional acceleration. Skilled human movements often demonstrate motor equivalence, which refers to the capability of the motor system in re-organising the available movement parameters in order to achieve the same motor outcomes (Hebb, 1949; Newell & Corcos, 1993). In our case, the perception of lower string tensions by expert players stimulated the expert motor system to alter the striking motion by increasing the flexion of wrist and fingers during impact, so that the additional speed can be generated to maintain high speed of the shuttlecock after impact. However, this method for generating additional speed comes with a cost: it takes more energy and may cause fatigue. For this reason, high string tensions are preferred by the experts.

To investigate whether the expert players did employ this strategy to yield the consistent shuttlecock speeds despite variations in string tensions, an additional analysis was performed. If the racquet was swung to make contact with the suspended shuttlecock at a constant angle, increasing the flexion of wrist and fingers during impact would result in a directional change of travel of the shuttlecock after impact (travelling downward more). The expert strokes were analysed with respect to two angles: the angle of the racquet at the moment of contact (“α” in Figure 3), and the angle of the shuttlecock after impact (“β” in Figure 3), reflecting the directional change of travel.

This analysis was performed using only the extremes of string tension variations: the lowest (16 and 18 lbs) and the highest (28 and 30 lbs) string

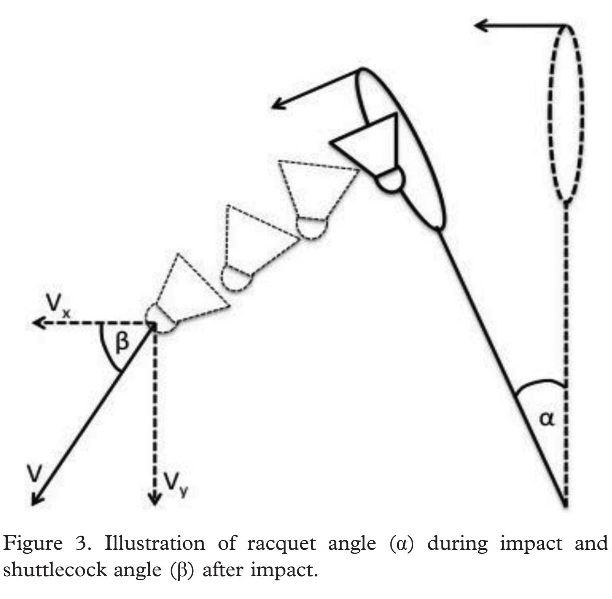

Figure 3. Illustration of racquet angle (α) during impact and shuttlecock angle (β) after impact.

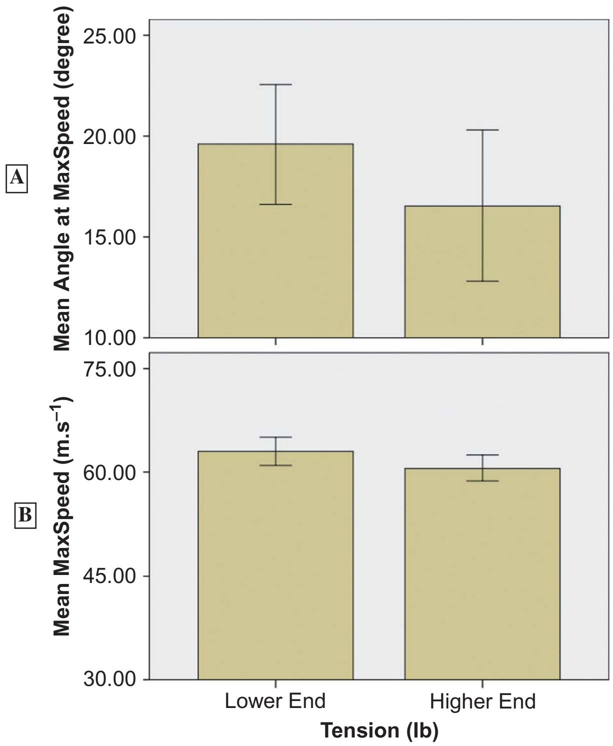

Figure 4. The mean angle and mean maximum speed of the shuttlecock after impact as a function of string tension for expert strokes. Error bars represent standard error of the mean.

tensions. As revealed by a one-way repeated measures ANOVA, the string tension did not affect, α, the angle of the racquet at the moment of contact, (F (1, 3) = 0.86, $P > 0.05$). The mean α was 21.5 degrees (±7.7). However, a change in β to a greater downward angle for lower string tensions was significant, (F (1, 3) = 14.07, $P < 0.05$, $\eta^2 = 0.82$).

As shown in Figure 4A, lower string tension corresponded to a greater mean angle, suggesting that expert players flexed their wrist and fingers more. The same ANOVA performed on the speeds yielded no tension effect, (F (1, 3) = 8.90, $P > 0.05$), as shown in Figure 4B. This confirmed that the extra flexion of wrist and fingers used to accommodate the lower string tension was effective in generating equally fast shuttlecock speeds as with higher string tension. This analysis suggests that expert players should be considered successful in perceiving the affordance of string tension, because by selecting the higher string tensions, they would not have to increase flexion of wrist and fingers (at greater cost in energy) to produce effective power strokes.

It is worth noting that selection of the optimal string tension was equivalent across different perceptual modes. Although the mean preferred tensions varied depending on motor expertise, no mean change was found for different perceptual modes, suggesting that similar tension can be perceived by listening to the sound of impact, by watching the bouncing event, or by pressing the string bed. Warren et al. (1987) compared use of visual and auditory perception of the elasticity of bouncing balls, and found that human observers could accurately judge the elasticity and then use that information to control performance of a bounce pass with the balls. Our results replicated this finding and showed in addition that the elasticity could be perceived haptically as well. The same tensions were subsequently chosen after hitting where the three modes could have been combined. The variability of the judgments indicated, however, that haptic perception of string tension was less reliable. Players are more experienced in both hearing and seeing the effects of string tension on power strokes and our results may simply reflect this fact. The findings are also consistent with the hypothesis of specification in the global array. According to Stoffregen and Bardy (2001), perceptual information is specified solely in the global array, where the higher-order relations exist across different forms of energy. In this sense, the perceptual information about the optimal string tension must exit in visual, acoustic, haptic, or the mixed arrays, and can be specified by the pattern of energy exhibited in each perceptual event presented to the perceiver. The perceivers must have picked up the same information from different arrays to detect the same optimal string tension. However, different frames of reference might be used depending on the experience of the perceiver, which resulted in different optimal tensions selected by players at different levels of expertise.

Finally, it was clear in our results that the meaning of string tension to badminton players depended on their motor expertise. For novice players, lower string tensions were better, but they failed to perceive this well. Presumably, as novice players develop motor expertise, the affordance of string tension for a power stroke becomes more salient and better perceived. It changes accordingly from the lower tensions to the higher, which were selected in common by recreational and expert players. The affordance itself was a function of skill level as was the ability to perceive the affordance. The nature of the affordance continued to change with continued development of skill from recreational to expert players. The meaning of true expertise emerged as an ability to perceive changes in the affordance of string tension and to modify one's action appropriately, but at a cost. However, additional research will be required to confirm this last conclusion.

In sum, we showed that badminton string tension constrained striking performance of the power stroke for novice and recreational players, but not for expert players. Player's perception of the optimal string tension was equivalent across different perceptual modes. The perception of the affordance of string tension for a power stroke was dynamic in that the affordance property became salient to players as motor expertise developed, but also changed itself. When motor expertise was enhanced to allow for more possibilities for action, energy efficiency became an important factor in determining the affordance of string tension.

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