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Original research

The effect of racquet swing weight on serve kinematics in elite adolescent female tennis players

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ABSTRACT

Objectives: Collision models for hitting implements denote how ball speed and swing weight increase proportionally when swing speed and impact location are held constant. The biomechanical effects of swing weight interventions are less understood. This study examined the effects of swing weight on serving arm mechanics, racquet kinematics, impact location and ball speed in the tennis serve.
Design: Repeated measures design, where racquet swing weight parameters distinguished between serve conditions.
Methods: Eleven elite adolescent female tennis players performed serves in three conditions: (1) regular, unperturbed racquet; (2) 5% increase in swing weight; and (3) 10% increase in swing weight. A 500 Hz Vicon motion analysis system captured three-dimensional serving arm, racquet and ball kinematics.
Results: When racquet swing weight was increased, the peak shoulder internal rotation and wrist flexion velocities during the forwardswing both decreased. The peak accelerations of shoulder internal rotation, elbow extension and wrist flexion also appeared to share an inverse relationship with swing weight. As swing weight increased, the impact location shifted significantly closer to the racquet tip and resultant racquet at impact decreased. Ball speed remained similar in all conditions.
Conclusions: The assumptions underlying the collision model appear to be violated by the biomechanical effects of a swing weight intervention in a sample of elite adolescent female players. Consequently, added swing weight fails to effect faster serves. From a dynamical systems perspective, the inherent response of the movement system deserves consideration prior to, and during, the administration of swing weight interventions.

1. Introduction

Coaches have a sense of responsibility to produce performance improvements in the players whom they coach. To this end, the development of hitting performance often involves refining movement patterns, enhancing conditioning or adjusting implement (racquet, bat, club, etc.) parameters. Regarding the latter, manufacturers distribute mass unevenly in tennis racquets and baseball bats to make them suited to different playing styles.[1] Qualitatively, coaches often direct implement selection according to a player's flair, even using artificial masses to manually adjust inertial parameters.[2] Simply put, when coaches wish to maximise ball speed, they will opt for end-loaded baseball bats[3] or add mass to the racquet tip,[4] as this is thought to increase the collision efficiency. While the theoretical principles behind such interventions are well described,[4] their validity in real-world performance has received far less research attention.

When serving in tennis, high resultant ball velocity (simply referred to as 'ball speed' in this article) is desirable for successful performance.[5] The importance placed on developing a proficient hitting action is therefore unsurprising. When aiming to improve a racquet's potential to produce a higher ball speed, the most effective location to add mass is at the tip,[4] as this increase its mass and swing moment of inertia (swing weight). Since added swing weight acts to increase the effective mass (M_{ef}) of the racquet at a given impact location (b),[6] the collision formula developed by Cross[7] depicts how a greater ball speed (V_b) will follow:

$$V_b = \frac{M_{ef} V_r (1 + e_A)}{M_{ef} + m} \tag{1}$$

where V_r is the racquet's resultant velocity at impact (or 'swing speed'), e_A is the collision efficiency (apparent coefficient of restitution) at the impact point and m is the mass of the ball. The work of Cross[4] and Cross and Nathan[8] has also confirmed that that added

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swing weight increases e_A at the impact locations relevant to a tennis serve.[4] Therefore, assuming that swing speed and impact location remain constant, added swing weight will produce a faster ball speed.[9,10] As such, the efficacy of swing weight interventions is largely contingent on swing speed and impact location remaining constant, as swing weight increases.

The complex, dynamic nature of the human movement system challenges the assumption that swing speed and impact location will remain constant during swing weight interventions. The constraints model described by Newell[11] proposes that emergent movement patterns are influenced by the interactive relationship of elements within the individual, task and environment. This concept forms the justification for the constraints-led instructional approach, where coaches deliberately manipulate task constraints to encourage the emergence of desired movements.[12] However, any constraints imposed upon the player (i.e. through racquet modification), act to disconcert their movement system, compelling the innate rearrangement of its component parts.[13] Therefore, the efficacy of swing weight interventions depends on how the component parts reorganize subsequent to the perturbation. Extant literature provides an insight into this reorganization, where swing speed has been shown to decline as swing weight increases in both tennis[7,14] and baseball.[15,16] Increased swing weight has also been proposed to compromise dexterity (how easily the implement can be wielded).[2] Further, swing weight has been shown to influence muscle activation patterns.[17] These findings dispute the assumed independence of swing weight and impact location. Indeed, measurement in situ has contested the physical models proposed to govern tennis racquet performance, wherein grip mechanics and racquet angular velocity are considered critical omissions.[18] Unsuitably, previous work has often examined the effect of swing weight on ‘dry swings’, which may not embody match performance[19] and obviously cannot consider impact location. Consequently, the relationship between increased swing weight and real-world performance remains ambiguous.

While coaching interventions are applied with the best intentions, it is important that they achieve their purported goal. To this end, constraints-led interventions that fail to adequately replicate the targeted skill (such as using an isolated ball toss to improve ball toss in the tennis serve) are considered potentially counterproductive.[19] Similarly, dynamical systems theory suggests that modifying swing weight will produce biomechanical changes in the service action. Accordingly, if increased swing weight perturbs the movement system to the detriment of swing speed and dexterity, the theoretical benefits of the intervention may never be realised in actual practice. Therefore, using the tennis serve as an exemplar hitting skill, the aim of this study was to assess the effect of increasing swing weight on serving arm and racquet kinematics, impact location and ball speed in elite adolescent females.

2. Methods

Eleven elite adolescent female tennis players provided informed consent to participate in this study, which was approved by the University of Western Australia’s (UWA) Human Ethics Committee. Adolescent players were chosen as this age group is commonly subjected to swing weight interventions. The players (mean age: 14.6 ± 0.7 years; height: 166.6 ± 4.7 cm; mass: 56.7 ± 3.8 kg) possessed a top 8 Australian ranking for their age group at the time of testing.

Data collection took place at an indoor biomechanics laboratory, wherein a temporary tennis court was constructed. Players were fitted with the UWA full body marker set[20,21] comprising sixty, 14 mm diameter retro-reflective markers. The racquet and ball were also fitted with three ultra-light hemispherical markers (radius 7 mm). Each player used her preferred racquet, of which the swing weight was measured prior to testing with a Prince Tuning Center (Prince Tennis, Bordentown, USA) and subsequently adjusted using Babolat lead tape. Players served in three separate conditions, which were differentiated by the modifications applied to their racquets: (1) regular, unperturbed racquet (NP); (2) 5% increase in swing weight (P_5); and (3) 10% increase in swing weight (P_{10}). These increases are consistent with practical interventions and previous swing weight analyses in tennis.[4] Players performed maximal effort first serves aiming for a 1 × 1 m target bordering the T of the service box (right-handers: deuce court; left-handers: advantage court) in all conditions. A 10-minute warm up with movement and serving components preceded the testing protocol. In the NP condition, players hit five blocks of eight serves, with a 2-minute rest period separating successive blocks. Players were then permitted a 10-minute rest before performing both the P_5 and P_{10}, which were assigned in a blinded, counterbalanced manner. In each of the P_5 and P_{10} conditions, players performed three blocks of eight serves, the first of which was considered a ‘familiarisation block’ to the nescience of the participants, and from which no serves were considered for analysis. Ethical consideration for the players’ physical wellbeing was the reason for the reduced number of serves in the P_5 and P_{10} conditions.

A 500 Hz, 22-camera VICON MX system (VICON Motion Systems, Oxford, UK) tracked three-dimensional (3D) marker trajectories relative to a global reference frame originating at the centre mark on the baseline. In the global coordinate system, positive x, y and z corresponded to right (parallel to the baseline), forward (toward the net) and upward, respectively. Five of each player’s fastest serves landing in the target area were selected for analysis in the NP condition. The reduced number of serves in the P_5 and P_{10} conditions prevented several players from achieving five successful serves, therefore only the three fastest serves landing in the target area were selected for analysis in these conditions.

A cubic spline interpolated gaps in the raw marker trajectories. A second-order polynomial extrapolation resolved the deleterious effects of filtering through impact.[22] Data from the body and racquet markers were filtered using a Woltring filter with the optimal mean squared error of 2 mm determined by a residual analysis, before being modelled using the UWA upper body, racquet and ball models.[23] Ball speed and impact location of the ball on the racquet face were determined by modelling the raw data, whereby impact was considered to occur at the nadir of ball origin’s x displacement in the racquet’s coordinate system (Fig. 1). Joint rotations were expressed using the Euler ZXY sequence, except at the shoulder where the International Society of Biomechanics’ recommended YXY decomposition was used.[24] Kinematics for the left-handed players were inverted where appropriate such that all players could be considered as right-hand dominant.

Variables of interest focused on the purported outcomes of swing weight interventions, the most relevant being ball speed. The marker on the racquet tip was used to measure the resultant velocity of the racquet at impact (swing speed), relative to the global reference frame. The location of the ball’s impact on the racquet face was determined by reporting the position of the ball origin, with respect to the reference frame of the racquet. The racquet’s reference frame originated in the centre of the strings with the x-axis pointing forward, the y-axis pointing toward the tip and the z-axis pointing rightward (Fig. 1). Each of the standard deviations of the ball’s impact location along the y- and z-axes of the racquet coordinate system were firstly doubled (to represent one standard deviation either side of the mean), before being multiplied together to produce the ‘impact area’ for each player. This value provided a within-subjects measure of the variability of the ball’s impact location on the racquet. During the forwardswing, peak shoulder internal rotation and wrist

Table 1
Mean and standard deviation (SD) kinematic variables of interest in the serving arm and racquet.

Variable	Unit	NP		P_5		P_{10}		ANOVA			
		Mean	SD	Mean	SD	Mean	SD	*F*	*p*	η_p^2	Post hoc
Peak internal rotation ω	deg s^{-1}	2165	373	1846	550	1724	297	3.742	0.042*	.272	††
Peak elbow extension ω	deg s^{-1}	1592	191	1545	183	1521	113	1.017	0.379	.092	
Peak wrist flexion ω	deg s^{-1}	1581	184	1314	326	1219	285	6.107	0.009*	.376	†,††
Peak internal rotation α	deg s^{-2}	117243	33727	95667	35771	84462	23860	4.488	0.025*	.310	†,††
Peak elbow extension α	deg s^{-2}	22836	4206	22722	3372	20847	3160	3.896	0.037*	.280	††,†††
Peak wrist flexion α	deg s^{-2}	69635	16822	41827	9021	37622	10391	26.675	0.000*	.727	†,††
Swing speed	m s^{-1}	40.7	2.8	40.1	2.5	39.8	2.2	9.524	0.001*	.488	†,††
Ball speed	m s^{-1}	41.5	3.1	41.2	2.2	41.4	3.0	0.218	0.806	.021	
Impact location on racquet (*Z*)	cm	−1.33	1.07	−1.45	1.24	−0.76	2.24	0.650	0.533	.016	
Impact location on racquet (*Y*)	cm	1.54	1.04	3.20	0.91	3.72	1.11	19.359	0.001*	.514	†,††

* Significant main effect ($p < 0.05$); significant post hoc effects: † NP vs. P_5; †† NP vs. P_{10}; ††† P_5 vs. P_{10}.

flexion velocities provided an insight into velocity generation, while peak accelerations of the same movements were used to gauge dexterity.

Repeated measures analyses of variance examined ten differences, wherein significance was fixed at $p < 0.05$. Effect size (denoted by partial eta squared, η_p^2) was also calculated for each comparison and interpreted as either small (0.2), medium (0.5) or large (0.8).[25] Post hoc Bonferroni analyses assessed differences between conditions.

3. Results

Peak shoulder internal rotation velocity decreased significantly from the NP to P_{10} conditions with the effect size ($\eta_p^2 = .272$) deemed small (Table 1). A small to moderate effect size ($\eta_p^2 = .376$) was noted for the significant decreased in peak angular wrist flexion velocity in both perturbation conditions, while peak elbow extension velocity was not affected by swing weight. In the serving arm, peak angular acceleration of shoulder internal rotation was significantly lower ($\eta_p^2 = .310$) in the P_{10} condition compared with the P_5 and NP conditions. Peak angular acceleration of elbow extension was also significantly lower ($\eta_p^2 = .280$) in the P_{10} condition. Peak angular acceleration of wrist flexion displayed a moderate to large effect size ($\eta_p^2 = .727$) and was significantly higher in the NP condition than the perturbation conditions.

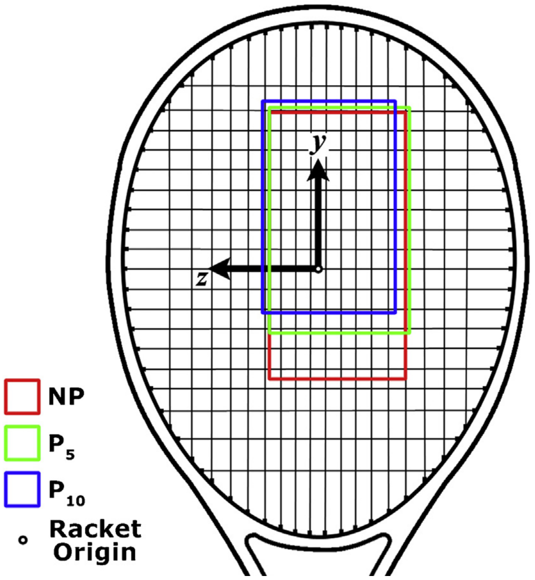

Fig. 1. Group mean impact areas for the three conditions (group mean impact location lies in the centre of each area).

A moderate effect size ($\eta_p^2 = .488$) was evident for the significant decrease in swing speed in the P_5 and P_{10} conditions. Ball speed was not affected by swing weight. Mean lateral impact location on the racquet face did not differ between the three conditions. However, impact did shift significantly toward the tip in the perturbation conditions, wherein a moderate effect size ($\eta_p^2 = .514$) was noted. The impact area ranged between 123 cm^2 and 159 cm^2 across the three conditions (Fig. 1).

4. Discussion

The results of this study provide an evidence-based insight into a contemporary and widespread coaching intervention. It appears that, during actual performance of the serve, the proposed positive benefit of the swing weight intervention was not realised in these elite female players. Namely, increased swing weight failed to effect an increase in ball speed.

Increased swing weight impeded internal rotation and wrist flexion in the serve and indicates how racquet modification can alter technique. In the serve, where these two movements are the largest contributors to resultant racquet velocity at impact,[26] these mechanical changes do not seem conducive to the intervention's purported benefits. Additionally, the shoulder internal rotation and wrist flexion velocities in these adolescents actually regressed toward what is seen in pre-pubescent players.[27] These mechanical changes are illustrative of the reorganisation of degrees of freedom that is proposed to accompany movement system perturbations,[13] and likely accounts for the decreased swing speed in both perturbation conditions. The tendency for players to alter their swing pattern challenges the assumption of consistency that underlies this intervention and hence deserves practical consideration.

With ball position shown to conservatively lie anywhere within a 408 cm^3 area,[27] players require precise control of the racquet leading up to impact to adjust to the variable ball position. Brisk compensatory movements in the distal joints prior to impact are considered critical this process,[28] where precise control of the racquet is essential. The significant decreases in joint accelerations that generally accompanied greater swing weights may lend support to the contention that increased swing weight affects dexterity.[2,29] If added swing weight indeed compromises control of the racquet, executing precise adjustments prior to impact would logically become more difficult. Accordingly, so would maintaining accurate, high velocity serves – possibly explaining why mean accuracy fell from 34% in NP to 30% P_5 and then 23% in P_{10}. Future research could evaluate this further by considering the enduring effect of swing weight on ball speed and accuracy (i.e. first serve percentage).

As swing weight increases, the upper extremity is required to generate more torque to swing the implement. Therefore, the decreased angular accelerations observed in the serving arm may have manifested because players lacked the strength to overcome the larger swing weight. This would endorse the suspicions of sports medicine practitioners, who have contended that equipment influences overload conditions of the upper extremity, such as humeral stress (I. Prangley, personal communication, October 31, 2011). Consequently, implement selection should be tailored to suit junior players' strength and/or anthropometry. Likewise, appropriate strength training may act to augment the efficacy of this intervention. Future work linking swing weight to muscle or joint loading, perhaps supplemented with preceding and/or concurrent strength programs would advance understanding in this domain.

The findings of perhaps the most applied interest are the ball speeds in the three conditions where the swing weight intervention failed to achieve its primary motive – an increase in ball speed. Akin to previous work investigating the tennis serve,[7] softball batting[17] and overhand swinging of metal rods,[7,14,16] swing weight increased to the detriment of swing speed in the present study. This is likely a product of the reduced contributions from the shoulder and wrist. The fact that a commensurate decrease in ball speed was not observed suggests that the decrease in swing speed was offset by the increase in racquet mass, a more efficient impact, or both.

The benefits of increased swing weight are understood to materialise when swing speed and impact location are unchanged. As impact occurred anywhere within a mean $\approx 397.86\,\text{cm}^2$ area on the racquet face in NP serves, it seems imprudent to assume that impact location is constant even in regulation serves. This notion is offered further support by previous work that suggests dexterity is compromised by swing weight.[2,29] Consequently, the assumed consistency of impact location during swing weight interventions seems counterintuitive. Indeed, the mean impact location shifted significantly closer to the racquet tip in the perturbation conditions, challenging the theoretical premise of the intervention. The work of both Brody[30] and Cross[4] shows that the location of maximum power transfer moves closer to the racquet tip as swing weight increases. Since the impact location shifted in this direction in the P_5 and P_{10} conditions, it offers support to the contention that decreased swing speed was offset by a more efficient collision. This benefit appears redundant within the context of the intervention however, as the increased swing weight ultimately failed to yield its purported reward.

The fundamental vibration node is also known to shift toward the racquet tip when mass is added to the racquet tip.[4] With previous work noting how skilled tennis players are sensitive to haptic information when wielding racquets,[29] the shift in impact location in both perturbation conditions may have followed the shift in the centre of percussion.[4] In this way, players could maintain consistent racquet vibration ('feel' of the stroke) as swing weight increased – supporting the assertion that this is an important feedback mechanism.[29] Ultimately, it appears essential to consider a player's natural impact location on the racquet prior to administering this intervention, as shifting impact location further from the point of maximal power transfer may prove detrimental.

Given that this was the first study to examine the biomechanical effects of swing weight, the variables of interest were delimited to the most obvious determinants of performance. Consequently, it could be reasonably expected that variability at the joint level increased, yet this was not examined. Future work may therefore wish to probe the effects of task constraints on movement variability. It is also worth noting that this study limited its assessment to the immediate effects of racquet perturbations. Future work should consider the longitudinal or training effects of swing weight interventions on both ball speed and technique. Similarly, this study only considered increases in swing weight of 5% and 10%, and therefore future work may wish to probe increases in swing weight <5%. Finally, other constraining factors such as racquet stiffness, grip force, string tension and string pattern may affect the efficacy of this intervention, and could be considered in future studies.

5. Conclusion

The physical models describing implement-ball collisions are irrefutable, thus the prevalence of swing weight interventions is understandable. However, the functional effects of this coaching intervention are seldom considered prior to its administration. This study found that the upper extremity joint mechanics critical to velocity generation and racquet dexterity are affected when swing weight is increased above a self-selected value. These factors logically contributed to the decrease in swing speed and shift in impact location that accompanied greater swing weights. Consequently, in these elite adolescent female players, the intervention failed to immediately achieve its purported goal – an increase in ball speed. Evidently, the complex, dynamic nature of the human movement system challenges the notion of increasing swing weight and reaping immediate rewards. Therefore, in administering this intervention, the organismic factors that constrain performance including strength capacities and technique should be considered a priori.

Practical implications

- Increasing a tennis racquet's swing weight by 5–10% significantly influences upper extremity mechanics in the tennis serve and fails to yield an immediate increase in ball speed.
- Strength training should precede and accompany swing weight interventions to improve the potential for a successful outcome.
- The dynamic human movement system prevents the unconditional application of collision models in tennis.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jsams.2013.03.001.

References

1. Trabert T, Witchery R, DeNevi D. Upgrading your equipment, In: *Tennis past 50*. Champaign, IL, Human Kinetics, 2002.
2. Lindsey C, Brody H. Weight, balance & swingweight, in *The physics and technology of tennis*, Brody H, Cross R, Lindsey C, editors, Solana Beach, CA, Racquet Tech Publishing, 2002, p. 23–35.
3. Bahill A. The ideal moment of inertia for a baseball or softball bat. *IEEE Trans Syst Man Cybern A Syst Hum* 2004; 34(2):197–204.
4. Cross R. Customising a tennis racket by adding weights. *Sports Eng* 2001; 4:1–14.
5. Haake S, Rose P, Kotze J. Reaction time testing and grand slam tie-break data, in *Tennis science and technology*, Haake J, Coe A, editors, Oxford, UK, Blackwell Science, 2000, p. 269–276.
6. Brody H, Cross R, Lindsey C. *The physics and technology of tennis*, Solona Beach, CA, Racquet Tech Publishing, 2002.
7. Cross R, Bower R. Effects of swing-weight on swing speed and racket power. *J Sports Sci* 2006; 24(1):23–30.
8. Cross R, Nathan A. Performance versus moment of inertia of sporting implements. *Sports Technol* 2009; 2:7–15.
9. Noffal G. Where do high speed tennis serves come from? *Paper presented at international symposium on biomechanics in sport*, 1999.
10. Brody H. How would a physicist design a tennis racket? *Phys Today* 1995; 48:26–31.
11. Newell K. Constraints on the development of coordination, in *In motor development in children: aspects of coordination and control*, Wade M, Whiting H, editors, Boston, Martinus Nijhoff, 1986, p. 341–360.

12. Renshaw I, Chow J, Davids K et al. A constraints-led perspective to understanding skill acquisition and game play: a basis for integration of motor learning theory and physical education praxis? *Physical Education & Sport Pedagogy* 2010; 15(2):117–137.
13. Davids K, Button C, Bennett S. *Dynamics of skill acquisition: a constraints-led approach*, Champaign, IL, Human Kinetics, 2008.
14. Mitchell S, Jones R, King M. Head speed vs racket inertia in the tennis serve. *Sports Engineering* 2000; 3:99–110.
15. Nathan A, Crisco J, Greenwald R et al. A comparative study of baseball bat performance. *Sports Engineering* 2011; 13(4):153–162.
16. Smith L, Broker J, Nathan A. A study of softball player swing speed, in *Sports dynamics: discovery and application*, Subic A, Trivailo P, Alam F, editors, Melbourne, Australia, RMIT University, 2003, p. 12–17.
17. Rogowski I, Creveaux T, Faucon A et al. Relationship between muscle coordination and racket mass during forehand drive in tennis. *Eur J Appl Physiol* 2009; 107(3):289–298.
18. Hennig E. Influence of racket properties on injuries and performance in tennis. *Exerc Sport Sci Rev* 2007; 35(2):62–66.
19. Reid M, Whiteside D, Elliott B. Effect of skill decomposition on racket and ball kinematics of the elite junior tennis serve. *Sports Biomech* 2010; 9(4):296–303.
20. Besier T, Sturnieks D, Alderson J et al. Repeatability of gait data using a functional hip joint centre and a mean helical knee axis. *J Biomech* 2003; 36(8):1159–1168.
21. Lloyd D, Alderson J, Elliott B. An upper limb kinematic model for the examination of cricket bowling: a case study of mutiah muralitharan. *J Sports Sci* 2000; 18(12):975–982.
22. Reid M, Campbell A, Elliott B. Comparison of endpoint data treatment methods for estimation of kinematics and kinetics near impact during the tennis serve. *J Appl Biomech* 2012; 28(1):93–98.
23. Whiteside D, Chin A, Middleton K. The validation of a three-dimensional ball rotaiton model. *Proc Inst Mech Eng P J Sports Eng Technol* 2013; 227:49–56.
24. Wu G, van der Helm F, Veeger H et al. Isb recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—part II: shoulder, elbow, wrist and hand. *J Biomech* 2005; 38(5):981–992.
25. Cohen J. *Statistical power analysis for the behavioral scixences*, 2nd ed New Jersey, Lawrence Erlbaum, 1988.
26. Elliott B, Marshall N, Noffal G. Contrubutions of upper limb segment rotations during the power serve in tennis. *J Appl Biomech* 1995; 11:433–442.
27. Whiteside D, Elliott B, Lay B, et al. The effect of age on discrete kinematics in the elite female tennis serve. *J Appl Biomech*, http://journals.humankinetics.com/jab-in-press/jab-in-press/the-effect-of-age-on-discrete-kinematics-of-the-elite-female-tennis-serve, in press.
28. Whiteside D, Elliott B, Lay B, et al. A kinematic comparison of successful and unsuccessful tennis serves along the elite development pathway. *Hum Movement Sci*, submitted for publication.
29. Davids K, Bennett S, Beak S. Sensitivity of children and adults to haptic information in wielding tennis rackets, in *Interceptive actions in sport*, Davids K, Savelsbergh G, Bennett S, et al., editors, New York, Routledge, 2002.
30. Brody H. The physics of tennis iii. The ball–racket interaction. *Am J Phys* 1997; 65(10):981–987.