



# The effects of ball impact location and grip tightness on the arm, racquet and ball for one-handed tennis backhand groundstrokes

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## ABSTRACT

A torque-driven, 3D computer simulation model of an arm–racquet system was used to investigate the effects of ball impact location and grip tightness on the arm, racquet and ball during one-handed tennis backhand groundstrokes. The stringbed was represented by nine point masses connected to each other and the racquet frame with elastic springs and three torsional spring–dampers between the hand and the racquet were used to represent grip tightness. For each perturbation of nine impact locations and grip tightness, simulations were run for a 50 ms period starting with ball–racquet impact. Simulations showed that during off-centre impacts below the longitudinal axis of the racquet, the wrist was forced to flex up to 16° more with up to six times more wrist extension torque when compared to a centre impact simulation. Perturbing grip tightness had no substantial effect on centre impact simulations. However, for off-centre impacts (below the longitudinal axis of the racquet) a tight grip condition resulted in a substantial decrease in racquet rotation within the hand (less than 2°) and an increase of 6° in wrist flexion angle when compared to the equivalent simulation with a normal grip. In addition there was approximately 20% more wrist extension torque when compared with equivalent off-centre impact simulation with a normal grip. Consequently off-centre impacts below the longitudinal axis of the racquet may be a substantial contributing factor for tennis elbow injuries with a tight grip aggravating the effect due to high eccentric wrist extension torques and forced wrist flexion.

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## 1. Introduction

The location of ball–racquet impact and grip tightness have a direct effect on the racquet/arm motion and the joint torques exerted during tennis strokes. Impacts frequently occur off-centre of the racquet head and it is common to have off-centre impacts even for experienced players (Elliott, 1982; Knudson, 1993). Off-centre impacts away from the longitudinal axis of the racquet result in less accurate rebounds (Knudson, 1993) and could contribute to elbow pain, especially in one-handed tennis backhands (Bernhang et al., 1974; Hennig et al., 1992; Giangarra et al., 1993; Roetert et al., 1995; Glynn et al., 2007). An effective backhand groundstroke, in its various forms, together with the forehand and serve comprises the fundamentals of baseline play (Elliott et al., 1989). Given its importance and the propensity for associated injury it is not surprising that the biomechanics of slice and topspin backhand strokes have been studied by a number of authors (Knudson, 1989, 1991a; Elliott et al., 1989; Giangarra

et al., 1993; Blackwell and Cole, 1994; Elliott and Christmass, 1995; Knudson and Blackwell, 1997; Wang, 1998; Riek et al., 1999; Wu et al., 2001).

To avoid upper extremity injury players must be able to endure the combination of external forces from the racquet and internal forces/torques generated by the muscles to move the racquet/arm system (Elliott, 2006). Eccentric contraction of the wrist extensor muscles during the one-handed backhand ground stroke is likely to be a key injury mechanism for tennis elbow (Blackwell and Cole, 1994; Knudson, 2004) with increased extensor activity found during ball–racquet impact for players with tennis elbow (Kelley et al., 1994; Bauer and Murray, 1999). Novice tennis players have a greater incidence of tennis elbow and generally tend to execute the one-handed backhand ground stroke with a flexed wrist and a wrist flexion angular velocity at the instant of ball–racquet impact (Blackwell and Cole, 1994; Riek et al., 1999).

During an off-centre impact, the racquet tends to rotate within the hand according to the ball–racquet relative velocity and the distance of the impact location to the longitudinal axis of the racquet. Grabiner et al. (1983) recommended a grip tight enough to prevent excessive rotation of the racquet. However, too tight a

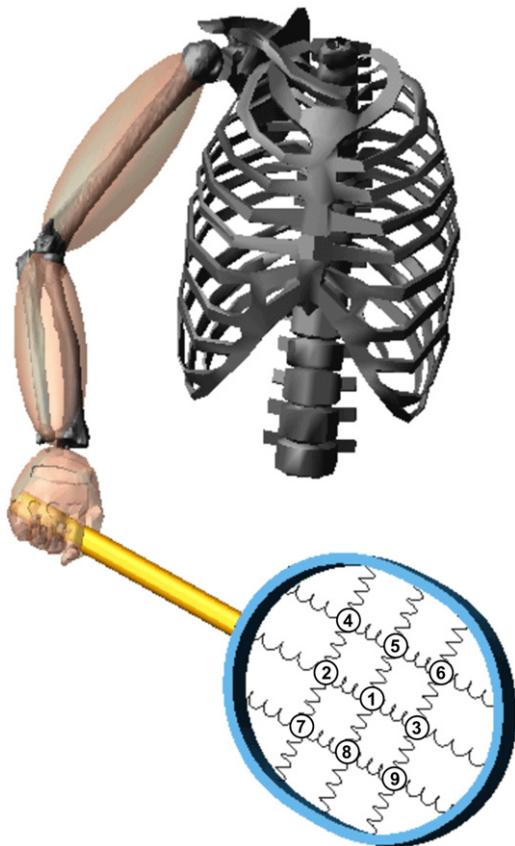
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grip may lead to muscle fatigue, reduced control and possible injury, since the hand tends to rotate with the racquet around the wrist for an off-centre impact (Roetert et al., 1995). Knudson (1991b) stated that, together with the pre-impact force on the hand, the impact location accounted for 66% of the variability of the post impact loading on the hand for forehand strokes. While Hennig et al. (1992) compared centre and off-centre impacts for backhand strokes and found an approximately threefold increase in arm loading during an off-centre impact.

To overcome the limitations of control during experimental studies, computer simulation models have been used to investigate tennis strokes. Nesbit et al. (2006) showed that off-longitudinal axis and off-latitudinal axis impacts substantially affected all elbow torque components while Glynn et al. (2007) found that compared to other variables impact location had the greatest effect on elbow loading. Both of these models were angle-driven and therefore could not simulate accurately arm and racquet movements for perturbations where they lacked motion data. In addition the relative effects of different off-centre ball impact locations and grip tightness on wrist/elbow kinematics and elbow loading are not clear. The purpose of this study was to investigate the specific effects of off-centre impacts and grip tightness on the ball, racquet and arm using a torque-driven computer simulation model.

## 2. Methods

A 3D subject-specific, torque-driven computer simulation model was used to simulate one-handed tennis backhand groundstrokes for a 50 ms period starting with the instant of ball–racquet impact. The model consisted of nine segments with three rotational degrees of freedom at the shoulder, two at the elbow, two at the wrist, three at the grip and two between the racquet handle and racquet head (Fig. 1). Seven pairs of torque generators (contractile component and an elastic



**Fig. 1.** Computer simulation model for one-handed tennis backhand strokes with the nine ball impact locations shown on the stringbed.

component in series (King et al., 2006)) were used to control joint angle changes with each pair of torque generators representing the torque exerted by the corresponding agonist–antagonist muscles across a joint. The torque exerted during a simulation was determined by multiplying maximum voluntary torque (9 parameter function of angle and angular velocity (King et al., 2006)) and the corresponding torque activation level (range 0–1; specified as a function of time using flexor and extensor torque activation profiles). The stringbed was represented by nine point masses and 24 linear springs were used to connect the point masses to each other and to the racquet frame. The ball could contact the racquet at any point mass location and simulate different ball impact locations (Fig. 1). Grip tightness between the hand and the racquet and the racquet's resistance to motion within the hand were represented by three torsional spring–dampers around the axes parallel to the principal axes of the tennis racket (Kentel et al., 2011).

The simulation model used has previously been evaluated by matching a one-handed backhand stroke by an elite male tennis player with realistic simulations produced for both centre impact and off-centre impact simulations (Kentel et al., 2011). In this study, the starting point of all simulations was a simulation that matched a centre impact stroke (Kentel et al., 2011). Torque activation profiles, initial conditions and subject-specific parameters (Glynn et al., 2011) were kept constant apart from the specific variable being investigated. Ball impact location was perturbed and eight off-centre simulations were run (plus the original centre impact simulation) corresponding to the nine impact locations on the stringbed (Fig. 1). Grip tightness was then varied over a large range (from the state of almost no grip to essentially a rigid connection between the hand and the racquet) for an off-centre impact location (location 9, Fig. 1). Based upon these initial grip tightness simulations, the centre impact matching simulation and two transversal off-centre impact simulations (locations 5 and 8, Fig. 1) were then perturbed to simulate a “tight grip” (50 times the matching simulation grip stiffness and damping) and a “loose grip” condition (0.5 times the matching simulation grip stiffness and damping). For all simulations the wrist flexion/extension angle and the racquet rotation about its longitudinal axis relative to the hand were compared along with the kinematics of the wrist flexor/extensor torque generators, the associated joint torques produced and the outbound ball velocity.

## 3. Results

The effects of ball impact location on racquet and wrist movement were clearly grouped corresponding to three impact location categories (Fig. 2); above the longitudinal axis of the racquet (locations 4–6), on the longitudinal axis of the racquet (locations 1–3) and below the longitudinal of the racquet (locations 7–9). The differences within the three impact location groups were found to be less than  $4.5^\circ$  for wrist flexion angle and less than  $6.5^\circ$  for racquet rotation about its longitudinal axis relative to the hand in the 40 ms period after ball–racquet impact. In addition, the difference in the wrist flexion/extension torque within each group was less than 4 N m. Impacts along the longitudinal axis of the racquet tended to have a smaller effect on the rotation of the racquet/wrist and the associated joint torques and forces, while ball impacts above/below the longitudinal axis had greater effects with the racquet forced to rotate about its longitudinal axis in opposite directions (Fig. 2b). The off-centre impacts also forced the wrist to extend excessively (up to  $10^\circ$  additional extension) for impacts on the upper part of the racquet (locations 4–6) and to flex excessively (up to  $16^\circ$  additional flexion) for the impacts on the lower part of the racquet (locations 7–9) compared with the original matched centre-impact simulation (Figs. 1 and 2a).

Forcing the wrist to extend/flex (in response to an off-centre ball impact) had a substantial effect on the exerted wrist flexion/extension torques (Fig. 2c) due to the changed internal kinematics of the extensor and flexor torque generators. In particular, high wrist flexion torques of up to seven times the equivalent matched simulation values were found for impact locations on the upper part of the racquet and high wrist extension torques of up to six times the equivalent matched simulation values were found for impact locations on the lower part of the racquet (Fig. 2c). Although similar magnitudes of wrist extensor and wrist flexor torques were found for contrasting off-centre impacts (Fig. 2c), the wrist flexion/extension joint angular velocity and the wrist

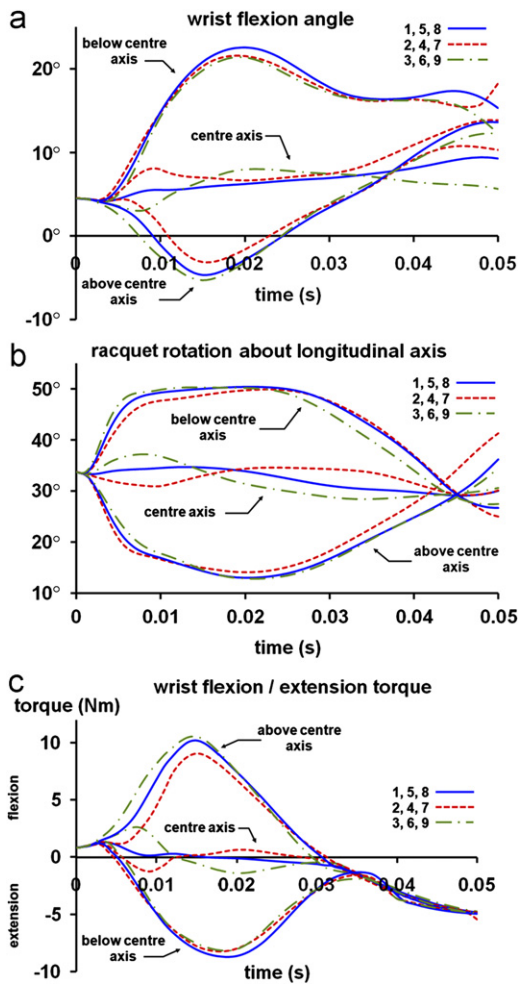


Fig. 2. Comparison of simulations at the nine ball impact locations on the tennis racquet. Net torque = wrist flexor torque – wrist extensor torque.

extensors contractile component angular velocity (for impact at the lower part; location 9, Fig. 3a) and wrist flexors contractile component angular velocity (for impact at the upper part; location 6, Fig. 3b) were found to be quite different. In particular, the angular velocities resulting from an impact at the lower part of the racquet were much higher than those obtained from an impact on the upper part of the racquet.

The maximum racquet rotation relative to the hand for an off-centre impact (location 9) was determined for different grip conditions (Table 1). Reducing the original matching simulation grip parameter values by more than 50% resulted in unrealistic racquet rotation (greater than 27° rotation of the racquet relative to the hand) for a loose grip. Increasing the grip parameter values beyond 50 times the matched values resulted in a very tight grip (less than 3° rotation of the racquet relative to the hand) and can be perhaps considered to be tighter than humanly possible, approaching a rigidly clamped condition.

Grip tightness had little observed effect on the matched centre impact simulation because the racquet rotation within the hand was relatively small for a centre impact regardless of grip tightness (Fig. 4). Increasing the grip tightness had a substantial effect on the wrist flexion/extension angle and racquet rotation around its longitudinal axis for off-centre impact simulations. For a tight grip, racquet rotation within the hand decreased substantially for both off-centre impacts to less than 2° (Fig. 4b) while the wrist flexion/extension angle increased (Fig. 4a). In addition off-centre impact simulations with a tight grip resulted in a wrist

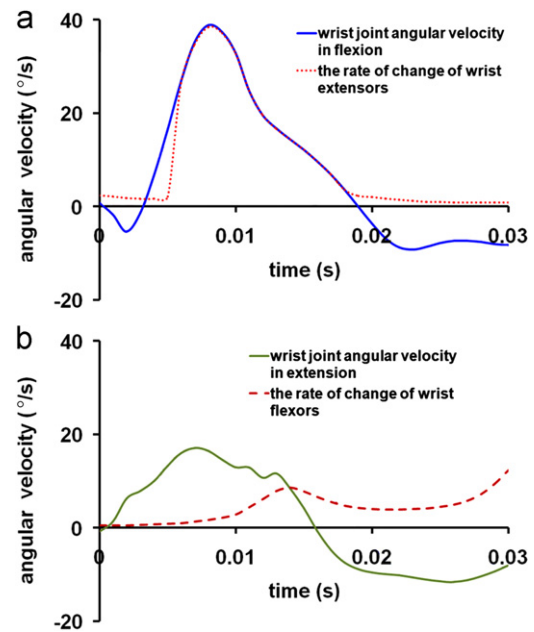


Fig. 3. (a) Wrist flexion angular velocity and the wrist extensors contractile component angular velocity for an impact at the lower part of the racquet (location 9); and (b) wrist extension angular velocity and the wrist flexors contractile component angular velocity for an impact at the upper part of the racquet (location 6).

Table 1

Maximum racquet rotation within the hand due to off-centre impact for several grip conditions obtained by multiplying matched visco-elastic parameter values.

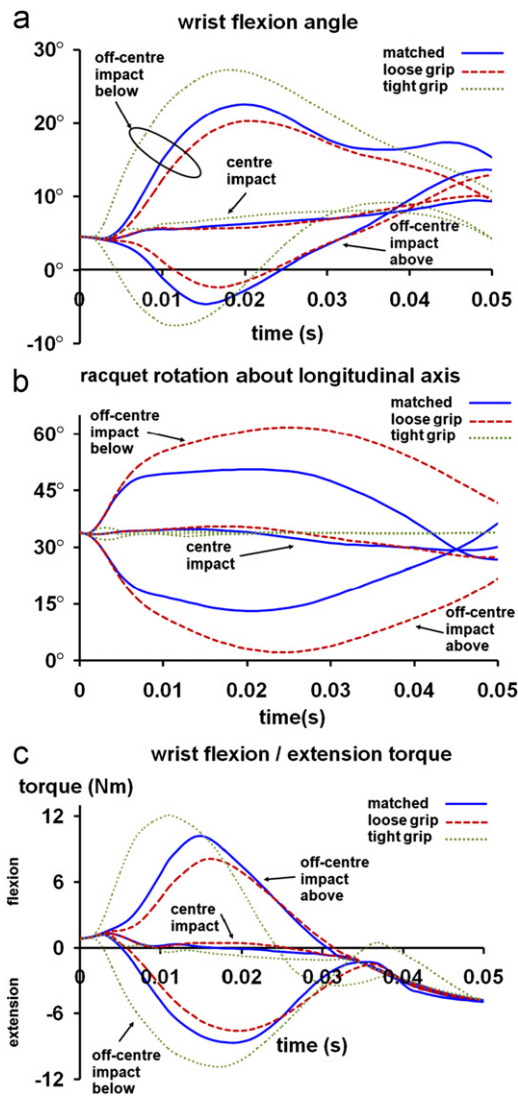
Grip tightness (multiple)	Maximum racquet rotation within the hand (deg.)
0.1	73.0
0.2	48.7
0.5	27.4
1	16.5
2	11.4
5	7.8
10	5.8
20	4.3
50	2.8
100	2.0

flexion/extension torque of around 20% higher than the magnitude of the maximum torque in the equivalent off-centre impact simulations with a normal grip (Fig. 4c). For off-centre impacts with a loose grip the opposite effect was found with more rotation in the hand and smaller changes in wrist flexion/extension angles than the corresponding simulations with a normal grip. In addition, it was noted that off-centre impact simulations with a loose grip were closer to the normal grip results than the corresponding tight grip simulations (Fig. 4).

No substantial change in the magnitude and direction of the ball rebound velocity for the nine impact locations was observed by varying grip tightness conditions. However, the rebound velocities of the impact points above and below the longitudinal axis were found to be smaller than those on the axis (Table 2).

#### 4. Discussion

The effects of off-centre impacts and grip tightness on the wrist and racquet during backhand groundstrokes were investigated using a 3D, torque-driven computer simulation model.



**Fig. 4.** Comparison of simulations with a tight, loose and normal (matched) grip for ball impact locations above (location 5), below (location 8) and on (location 1) the longitudinal axis of the racquet. Net torque = wrist flexor torque – wrist extensor torque.

**Table 2**

Magnitude and direction of the ball rebound velocity for different impact locations.

Impact location	$V_x$ (m/s)	$V_y$ (m/s)	$V_z$ (m/s)	$V$ (m/s)
1	2.6	27.0	6.2	27.9
2	3.0	26.1	6.2	27.0
3	2.3	27.2	6.0	28.0
4	2.5	21.7	5.0	22.5
5	3.0	23.4	5.4	24.1
6	3.5	22.6	5.0	23.4
7	2.4	21.7	5.6	22.5
8	2.7	23.3	6.1	24.2
9	3.0	22.4	6.3	23.4

Note: The orientation of the reference frame was arranged such that the incoming ball was in the  $-y$  direction and  $+z$  was vertically upwards.

Substantial increases in the wrist flexion/extension torque were found to occur for off-centre impact locations. The major kinematic change with respect to a centre impact simulation was observed in the racquet rotation about its longitudinal axis relative to the hand and the wrist flexion/extension angle.

Although off-centre impacts on the longitudinal axis of the racquet had small effects, impact locations above and below the longitudinal axis caused considerable increases in wrist extension and flexion, respectively. In addition, grip tightness had a substantial effect on off-centre impacts away from the longitudinal axis although little effect was observed for the impacts on the axis. In particular a tight grip increased the 'negative effects' of off-centre impacts considerably.

During off-longitudinal axis ball–racquet impacts, the torque applied to the racquet about its longitudinal axis results in an increase in the angular momentum of the racquet about its longitudinal axis. The resulting rotation of the racquet relative to the hand causes the grip torque applied to the racquet to increase and reduce the racquet angular momentum. In turn the reaction of the increased grip torque causes an increase in the angular momentum of the hand about the wrist joint. The subsequent rotation of the racquet–hand system relative to the forearm causes either the wrist extensors or flexors to be stretched (depending on whether the impact is below or above the longitudinal axis) with the effect of an increase in the wrist torque that resists the racquet–hand system angular motion and decreases its momentum. In particular, during off-centre impacts in the lower part of the racquet, the wrist flexion angle increased and the wrist extensor contractile component lengthened when compared to the centre impact matching simulation. Comparing the wrist joint flexion/extension angular velocity and wrist extensor contractile component angular velocity showed that for about a 10 ms period starting from approximately 5 ms after ball impact, the angular velocity of the joint and the angular velocity of the contractile component became almost equal since the rate of change of the wrist extensor torque was very small in this period (Fig. 3a). This was due to the wrist extensor torque generator essentially reaching peak torque due to the eccentric angular velocity of the contractile component being sufficiently high. In addition the wrist flexion torque decreased substantially due to concentric conditions, therefore the combination of increased extensor torque and decreased flexor torque resulted in a net effect of higher extensor torque at the wrist. Having a tight grip further increased the extensor torque since the wrist flexed more due to the considerably reduced racquet rotation within the hand. In contrast, impacts on the upper part of the racquet forced the wrist to extend and therefore eccentrically stretch the wrist flexors with a net effect of higher wrist flexor torques. However, the angular velocity of the contractile component of the wrist flexors was much lower than the wrist extensors for an off-centre impact in the lower part of the racquet and the wrist flexors did not reach the eccentric plateau level. The peak wrist extension and flexion torques for off-centre impacts were 24 N m and 29 N m, respectively, while the peak torques obtained from isovelocity measurements with the same subject were 31 N m and 63 N m, respectively. As a result although the wrist flexors reached a higher absolute torque it was a lower percentage of maximum (46% compared with 77%). The higher relative loading of the wrist extensors and the higher eccentric stretching velocity of the wrist extensor contractile component may help to explain why tennis players typically have more problems associated with their wrist extensor muscles than their wrist flexors even though both muscle groups are stretched eccentrically for off-centre impacts below and above the longitudinal axis of the tennis racquet, respectively.

High wrist extension torques come from eccentric contraction of the wrist extensor muscles including the *extensor carpi radialis brevis* (ECRB) muscle. Excessive use of wrist extensors causes microtrauma and microtears on the extensor tendons (generally ECRB tendon) which are associated with the tennis elbow (Riek et al., 1999; Nirschl and Ashman, 2003). This study suggests that

due to high wrist extension torques, off-centre impacts on the lower part of the racquet may be a substantial contributing factor for tennis elbow with a tight grip aggravating the effect. Furthermore recreational players who are likely to be weaker and hit the ball off-centre more often due to poor technique (Brody et al., 2002) would appear to be more likely to suffer from tennis elbow. In particular novice players have a greater incidence of tennis elbow and generally tend to execute the one-handed backhand ground stroke with a flexed wrist and a wrist flexion angular velocity at the instant of ball–racquet impact (Blackwell and Cole, 1994; Riek et al., 1999). In the future it would be appropriate to examine recreational players in more detail with a particular focus on the relationship between off-centre impacts, technique, strength and elbow pain. Furthermore, the issue of grip tightness warrants further investigation as it is not clear what a realistic range of grip tightness is for a specific player and how this range might vary for different players. Previously in the literature grip tightness has been likened to both a free and rigid condition (Kotze et al., 2000) with racquet model response assessed under both conditions. In this study two contrasting grip conditions; a very “tight grip” simulation and a very “loose grip” simulation have been compared with the matched grip tightness simulations. Using a large range of grip tightness and perturbing ball impact location has demonstrated that ball impact location has a large effect on wrist angles and torques (six to seven times increase in torque, Fig. 2c) with a tight grip aggravating the effect (around 20% increase in torque, Fig. 4c). Although grip tightness has been previously linked to injury (Wei et al., 2006) our results show that even with a very “loose grip” the player would experience adverse loading conditions for an off-centre impact suggesting that the frequency and severity of “mishits” is perhaps a greater risk factor for injury than grip tightness.

The results of this study were consistent with the previous studies (Hennig et al., 1992; Glynn et al., 2007) that indicate off-centre impacts cause higher arm loading. In particular, Nesbit et al. (2006) found substantial differences between centre and off-centre impacts during forehand strokes. However, angle driven models may overestimate joint forces and torques due to errors in the kinematic inputs to the model. Since the model presented here was torque-driven accurate simulations were possible for a range of impact locations and grip tightness conditions. This study suggests that due to high wrist extension torques, off-centre impacts on the lower part of the racquet may be a substantial contributing factor for tennis elbow with a tight grip aggravating the effect. In the future it may be possible to include subject-specific individual muscle representation instead of torque generators to enable more detailed investigations of the mechanisms which cause tennis elbow.

### Conflict of interest statement

There are no issues of conflict of interest arising from the personal or professional associations of any of the authors.

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