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Optimizing the Release Conditions for a Free Throw in Wheelchair Basketball

Brianne N. Schwark, Sasho J. Mackenzie, and Eric J. Sprigings
University of Saskatchewan

The primary purpose of this study was to determine the optimal release conditions and corresponding arm movement pattern for the free throw for players classified as 3 to 4.5 on the international player classification system in wheelchair basketball. A 2-D, three-segment simulation model was used to investigate this problem. The computational process involved a two-step optimization scheme in which an outer computational loop was used to optimize the magnitude and timing of the muscle torques that generate the arm's motion, and an inner computational loop was used to determine the optimal angle and speed of the ball at the moment of release. The inner optimization loop revealed that Brancazio's (1981) and Hay's (1993) approaches to determining the optimal release angle produced identical results. The lowered seated height of the wheelchair basketball player required that the ball be released at a steeper angle with greater vertical velocity, and hence the need for greater shoulder torque. For the wheelchair player, the peak shoulder flexion torque generated by the model was reduced by approximately 43% when the upper arm was initially positioned at an angle approximately 40° below the horizontal, as compared to being positioned at an angle of 10° above the horizontal. For the wheelchair player, the optimal release angle and speed for a ball released at a horizontal distance of 4.09 m from the center of the basket, and 1.30 m below the rim, was computed to be 53.8° and 7.4 m/s, respectively.

Key Words: simulation, optimization, muscle torques

The enjoyment we derive from participating in a sport is enhanced by improving our competence in that sport (Whiddon & Reynolds, 1983). In order to be successful in a sport, one must become proficient in the fundamental skills of the game (Malone, Nielsen, & Steadward, 2000). Many studies have addressed the optimal patterns for sport skills in order to increase this competence in athletes. However, the area of wheelchair sport has been greatly overlooked. Currently there are few published studies which have attempted to optimize skills in wheelchair sport (Goosey-Tolfrey, Butterworth, & Morriss, 2002).

The authors are with the College of Kinesiology, University of Saskatchewan, Saskatoon, SK, Canada S7N 5C2.

Since the inception of wheelchair basketball shortly after World War II, the game has evolved from being a rehabilitation exercise into a fast-paced sport that is played in over 75 nations (Malone et al., 2000). Wheelchair basketball is regarded as one of the highest profile disability sports (Goosey-Tolfrey et al., 2002). As the level of competition increases, players need better ways to optimize their game skills.

One such skill is that of free throw shooting. Wheelchair basketball players have consistently been found to have free-throw percentages approximately 20% less than those of able-bodied standing athletes of the same caliber (Kozar, Vaughn, Whitfield, Lord, & Dye, 1994; Owen, 1982). At the 1994 Men's World Championship, standing basketball players had free-throw shooting percentages of 59–83%, with a mean of 71%, whereas male wheelchair basketball players at the 1992 Paralympics in Barcelona had percentages of 35–54%, with a mean of 41% (Malone et al., 2000).

In wheelchair basketball, the functional level of the players can vary greatly depending on their spinal cord level of disability. For this reason, a classification system was developed to take into account their level of physical disability. The current international system divides players into eight classes (Class 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5) based on trunk movement and sitting balance (www.iwbf.org/classification/functions.htm). For example in shooting, a Class 1 player would be described as having a significant loss of stability in the trunk, whereas a Class 4.5 player is able to move the trunk forcefully in all directions.

To improve free-throw shooting percentage, the player must be able to consistently reproduce the combination of release speed and trajectory that will take the ball through the hoop. The first step in addressing this requirement is to identify the optimal speed and angle of trajectory for the free throw. This ideal combination of release conditions has been examined by several researchers for the standing free throw (Brancazio, 1981; Hamilton & Reinschmidt, 1997; Hay, 1993), each looking at the problem from a slightly different perspective. Brancazio (1981) examined how sensitive the distance of the projected ball was to both the release speed and the angle of release. His mathematical analysis indicated that controlling the speed of release was an order of magnitude more important than was controlling the angle of release in terms of making a successful basket. Brancazio concluded that the best release condition would result from using the lowest release speed capable of making a successful basket, and suggested this should be the easiest condition for the player to reproduce.

Hay (1993), on the other hand, calculated the release angle that would provide the greatest margin for error if the player deviated $\pm 1^\circ$ from this ideal release angle. In the most recent paper on the subject, Hamilton and Reinschmidt (1997) expanded on the number of independent variables that had been previously considered in determining optimal release conditions, including the spin of the ball and its effect on the ball's behavior when hitting the rim of the basket. However, their paper failed to take into consideration the relative difficulty that a player might have in consistently reproducing the higher release speed predicted by their model.

Malone, Gervais, and Steadward (2002) compared results recorded by wheelchair basketball players with the optimized results predicted by Brancazio's work (1981), but to date no one has modeled the optimal release conditions and associated joint torques that produce the desired movement sequence for a free throw in wheelchair basketball. Successful modeling of the optimal release conditions should make it possible, in a future study, to refine the shooting technique of wheelchair basketball players through superimposed video comparisons of their performances with the movement pattern displayed by the optimized model.

The purpose of this study was twofold: (a) to compare the approaches taken by Brancazio (1981), and Hay (1993), in terms of determining the optimal angle of projection for a basketball shot; and (b) to determine the optimal release conditions and corresponding optimal arm movement pattern in the free throw for players classified as 3 to 4.5 on the international player classification system in wheelchair basketball. It was hypothesized that for a wheelchair free throw the optimal release angle, as well as the torque generated at the shoulder, would have to increase markedly over that displayed for a standing free throw to compensate for the greater vertical distance to the basket.

Methods

The search for the optimal release conditions for the ball involved a two-step process. The first step was to develop a method that would compute, for a given distance from the basket, the optimal speed and angle of release of the ball. The second step was to determine the optimal arm motion that would generate this optimal ball speed and release angle for a successful basket. Computationally, this required two separate optimization loops running within the same program. The outer optimization loop was programmed such that at the moment of ball release, the instantaneous vertical and horizontal distances of the ball from the center of the basket were calculated. This distance information was then passed to the inner optimization loop subroutine, which in turn computed the optimal trajectory using Powell's optimization search (Press, Teukolsky, Vetterling, & Flannery, 1992) with Brancazio's minimum release speed as the objective function.

The corresponding optimal vertical and horizontal components of velocity computed by this subroutine were then passed back to the outer loop program for comparison with the actual vertical and horizontal components of the ball's speed at release. This difference was minimized in the outer loop using a second Powell subroutine. In both the inner and outer optimization searches, the sums of accrued penalty variables were included in the objective function to discourage searches in unrealistic directions. Thus, the outer optimization loop controlled the arm movement pattern up to the point of release, and the inner optimization loop determined the optimal speed and angle of release at the point of release.

The optimization scheme for the inner loop was selected after first comparing the approaches used by Brancazio (1981) and Hay (1993). Since both of these authors used different objective functions, the question arose as to whether their respective methods produced similar results. To answer this, both methods were programmed and their results were compared. Both methods required that the height and horizontal distance to the basket at release be known. For both methods, the release angle was used as a control variable, and the corresponding release velocity that would project the ball to the coordinates of the center of the basket was calculated. For Hay's method, the angle of release (and corresponding release speed) that produced the greatest error tolerance for successfully making the basket when the release angle was varied by $\pm 1°$, was used as the objective function. For Brancazio's method, the lowest release speed that would produce a successful basket without hitting the rim was used as the objective function.

The outer computational loop was designed to determine the optimal movement patterns of the arm segments that would produce the optimal release speed and angle of projection for the ball. In this simulation study it was assumed that the athlete being modeled was classified as 3 to 4.5 on the international classification system (www.iwbf.org/classification/functions.htm) and thus could provide adequate trunk stability during the free throw. With this understanding, the shoulder joint was fixed and the segments of the right arm moved in relation to this origin. The right arm of the wheelchair athlete, holding a basketball, was modeled as a 2-D, three-segment linked system comprising the upper arm, forearm, and hand + ball (Figure 1). The left arm was not included in the model since it was assumed to make no contribution to the propulsion of the ball, and that any directional stability it does provide would be easily handled through the 2-D constraint placed on the model.

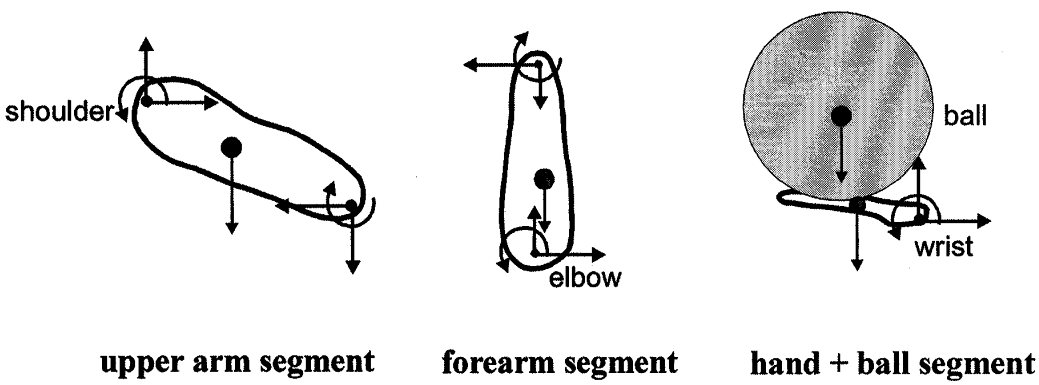

Figure 1 — Two-dimensional model, with muscle torque generators inserted at the shoulder, elbow, and wrist, used in simulating the wheelchair free throw. The origin for the system was located at the shoulder joint.

Torque actuators for the right arm were inserted at the proximal end of each segment and gave the model the ability to add energy to the system. The torque actuators used in the simulation were programmed to be constrained by the activation rate and force-velocity properties of human muscle (Sprigings & Neal, 2000). The force-length property of muscle was expected to play a second order role in the outcome of the performance (Caldwell, 1995) and, as such, was not included in the simulation model. Parameter values for segment length, moment of inertia, and mass for a representative player with a body mass of 80 kg, and a standing height of 1.83 m, were calculated using the values of De Leva (1996). The basketball was modeled as a spherical shell with a mass of 0.608 kg and a moment of inertia of 0.00618 kg·m^2 (Meriam, 1978).

The equations of motion for the three-segment system were written using a Newtonian formulation in combination with the known equations of constraint for a system linked with revolute joints.

Newtonian equations of motion for three-segment model

$$F_{xn} = \sum_{i=n}^{3} (m_i \, a_{xi}) \tag{1}$$

$$F_{yn} = \sum_{i=n}^{3} [m_i \, (a_{yi} + g)] \tag{2}$$

$$I_n \alpha_n = F_{xn} r_{2n-1} \sin(\theta_n) - F_{yn} r_{2n-1} \cos(\theta_n) + F_{xn+1} r_{2n} \sin(\theta_n) - F_{yn+1} r_{2n} \cos(\theta_n) + C_n - C_{n-1} \tag{3}$$

Equations of constraint for linked segment model

$$a_{xn} = \left\{ \sum_{i=1}^{n-1} [-\alpha_i L_i \sin(\theta_i) - \omega_i^2 L_i \cos(\theta_i)] \right\} - \alpha_n r_{2n-1} \sin(\theta_n) - \omega_n^2 r_{2n-1} \cos(\theta_n) \tag{4}$$

$$a_{yn} = \left\{ \sum_{i=1}^{n-1} [-\alpha_i L_i \sin(\theta_i) - \omega_i^2 L_i \cos(\theta_i)] \right\} + \alpha_n r_{2n-1} \cos(\theta_n) - \omega_n^2 r_{2n-1} \sin(\theta_n) \tag{5}$$

where:

F = external component of force on segment

x,y = coordinate axis direction

n = 1 to 3 where: 1 is the upper arm; 2 is the forearm; 3 is the hand + ball

a = linear acceleration of segment cm

m = segment mass

g = gravitational acceleration

I = moment of inertia of segment about its cm

α = absolute angular acceleration of the segment

r = length between segment's proximal or distal ends and its cm (e.g., r_1 = distance from shoulder joint to CM of upper arm, r_2 = distance from CM of upper arm to elbow joint, etc.)

θ = absolute orientation angle of the segment as defined counterclockwise from a right horizontal axis attached to its proximal end

C = internally generated muscle torque

L = total length of segment

ω = absolute angular velocity of segment.

The hand + ball segment was treated as a single segment up until the point of release. The moment of inertia of the hand segment was adjusted using the parallel axis theorem to account for the ball's additional inertial contribution. A fifth order Runge-Kutta-Fehlberg algorithm (Burden, Faires, & Reynolds, 1981) with variable step size was used to drive the simulation model (Sprigings, Lanovaz, Watson, & Russell, 1998).

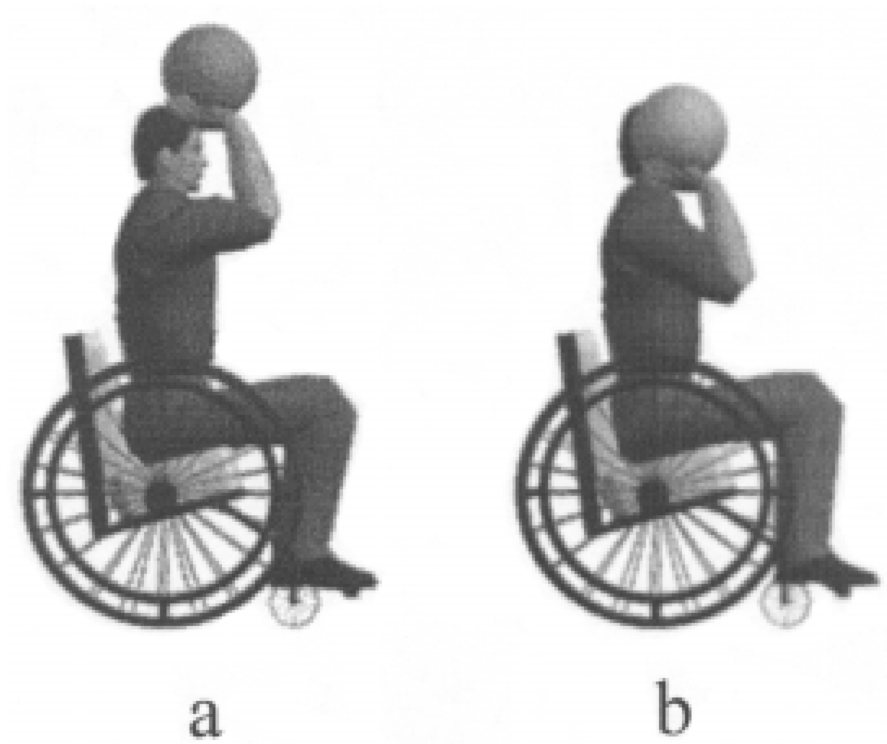

Figure 2 — Starting configurations for the 3-segment system. Fig. 2a represents a position that most likely would be adopted by an able-bodied player trying to replicate the shooting motion he/she uses from the standing position. Fig. 2b represents the position most commonly adopted by those familiar with shooting from a wheelchair.

Wheelchair simulation results were compared for two shooting strategies that employed different starting positions for the upper arm (Figures 2a, 2b). Six control variables were used to regulate the simulated movement pattern of the arm segments: time of onset of the activation for both the elbow and wrist muscle torque actuators (the muscle torque for the shoulder joint was assumed to begin at time zero); the time of release; and the maximum isometric torques used in the equations governing the torque output from each muscle actuator at the three joints. Prior to the dynamic activation of the muscle actuators at the elbow and wrist joints, the relative angles of the forearm and hand segments with respect to the upper arm were constrained to remain constant.

The validity of the simulation results was examined by comparing the image sequences and angular displacement patterns for the three-segment model with that of a real-life video record of a wheelchair free throw. In addition, the primary code for the three segments was assessed for programming errors by confirming that the total energy of the system remained constant in the absence of any muscle torques being applied to the system.

Results

A comparison of the two optimization approaches (Brancazio, 1981; Hay, 1993) revealed that, for any given distance from the basket, the same set of optimal release values (as measured to a computational accuracy of ± .001) was predicted.

For example, for a standing free throw in which the ball was released at a distance 0.918 m below the basket and at a horizontal distance of 4.570 m (the values used by Hay, 1993), the optimal speed and angle of release, as computed by both methods, was found to be 7.398 m/s and 50.684°, respectively. For a free throw taken from a wheelchair at the same horizontal distance, but 1.300 m below the basket, both optimization methods computed the optimal speed and angle of release to be 7.704 m/s and 52.939°, respectively.

The starting configurations of two different strategies for the three-segment system are shown in Figures 2a and 2b. The position shown in Figure 2a is a typical starting configuration that someone with experience shooting from a standing position might assume when attempting to shoot from a wheelchair. Figure 2b shows the starting position used by most veteran wheelchair basketball players. The reason for this difference is that most veteran players realize there is a need to create a significantly greater vertical release speed because of the greater vertical distance to the basket. In the starting configuration shown in Figure 2a, the upper arm has only a limited range of motion in which to develop the necessary vertical velocity at release. The short time period (0.113 s) corresponding to this limited range of motion necessitated the use of a large shoulder torque to produce the required velocity at release (Figure 3a).

On the other hand, when the simulation began with the starting configuration shown in Figure 2b, the time period of applying the torque was lengthened (0.181 s) and thus the magnitude of the shoulder torque was noticeably lower (Figure 3b). This resulted in the peak value of muscle torque at the shoulder joint being reduced by 25 Nm (43.5%) when the simulation was started from the position shown in Figure 2b. For both starting positions (Figures 2a, 2b), the same final release point in space was found to be optimal, which means that their corresponding optimal release speed and angle were virtually the same.

Stepping through the optimized simulation sequence of the wheelchair free throw one step at a time, it was observed that during the greatest gain in vertical velocity of the ball, only the shoulder torque generator was active (Figure 3b). Thus the shoulder flexion torque (counterclockwise in Figures 2a, 2b) was primarily responsible for producing the ball's vertical velocity at release. The clockwise torques at the elbow and the wrist joints were activated later in the movement sequence and were the primary controllers of the ball's horizontal velocity at release. The specific roles of the shoulder, elbow, and wrist torques are discussed in greater detail in the Discussion section below.

With the origin of the shoulder positioned 1.1 m directly above the free-throw line (which is legal according to the IWBF, 2002), the distance of the ball from the basket at release was computed to be 4.09 m horizontally and 1.3 m vertically. The optimal release speed and angle corresponding to this distance from the basket was computed to be 7.4 m/s and 53.8° (Figure 4). The angle of entry at the basket corresponding to this release angle was 36.2°. For slight deviations from this release angle, where the ball would strike the rim, the vertical velocity at rim contact would be –2.79 m/s. For the same horizontal distance, but from a standing position where the vertical distance to the basket at release was .918 m, the optimal speed and angle of release using Brancazio's criterion was calculated to be 7.08 m/s and 51.3°, respectively. The angle of entry corresponding to this release angle from the standing position was 38.7°. For slight misses, the vertical contact velocity of the ball at contact with the rim would be –3.18 m/s.

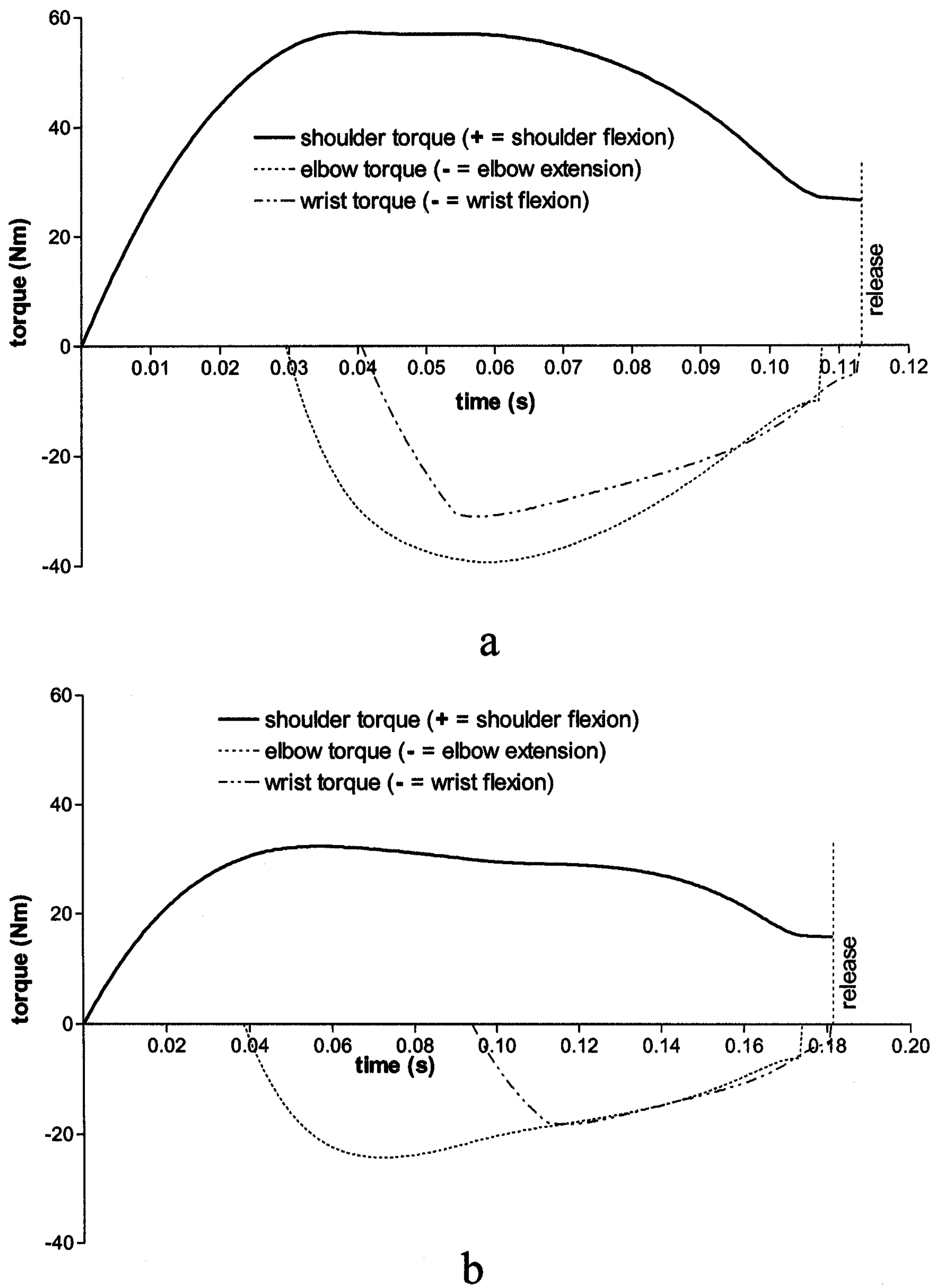

Figure 3 — Optimal torque histories from the three muscle torque generators using different starting positions. Fig 3a shows the torque histories produced by the model when starting from the position shown in Fig. 2a, while Fig. 3b shows the torque histories when starting from the position shown in Fig. 2b.

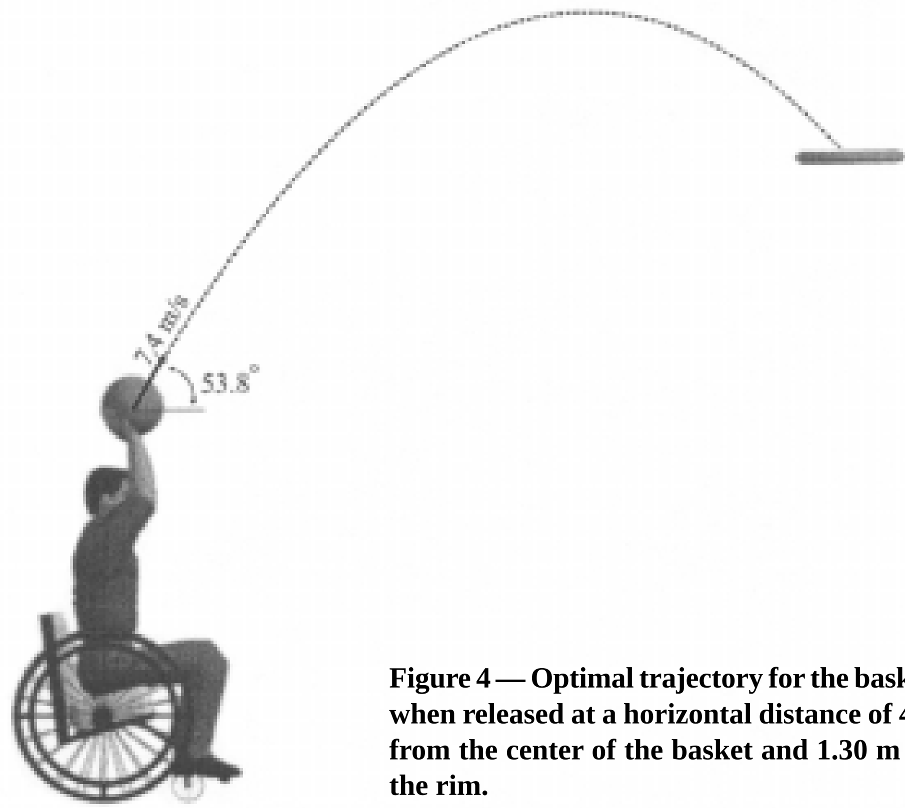

Figure 4 — Optimal trajectory for the basketball when released at a horizontal distance of 4.09 m from the center of the basket and 1.30 m below the rim.

The image sequences (Figures 5a, 5b), as well as the corresponding angular displacements of the arm segments (Figures 6a, 6b), were compared between a real-life wheelchair basketball player executing a free throw and the model's optimized simulation. The results revealed a similar but slightly different sequential pattern of movement for the arm segments. It is noticeable that the arm of the optimized model ended in a more vertical position at release than that of the real player. This can be attributed to the recognition by the optimizing algorithm that the higher finishing arm position actually reduced the magnitude of the release speed needed to get the ball to the center of the basket.

It should also be noted, when comparing the images, that the real player placed his left hand (not shown) on the side of the ball to keep it from rolling off the hand during the delivery phase, while the model assumed that only the right hand was touching the ball during this same phase. This most likely accounts for the observed difference in hand positions between the model and the real player during the early delivery phase of the ball. The time period from activation till release was the same (.18 s) for both the simulation and the real player. However, it is evident from the angular displacement histories that slightly different strategies were used. The simulation model delayed the elbow and wrist extension until the upper arm had produced most of the vertical velocity required for a successful basket, whereas the real player began the elbow extension and wrist flexion sooner, which resulted in a lower position of the upper arm at release. This lower release angle used by the real player demanded a release velocity that was greater than that deemed to be optimal.

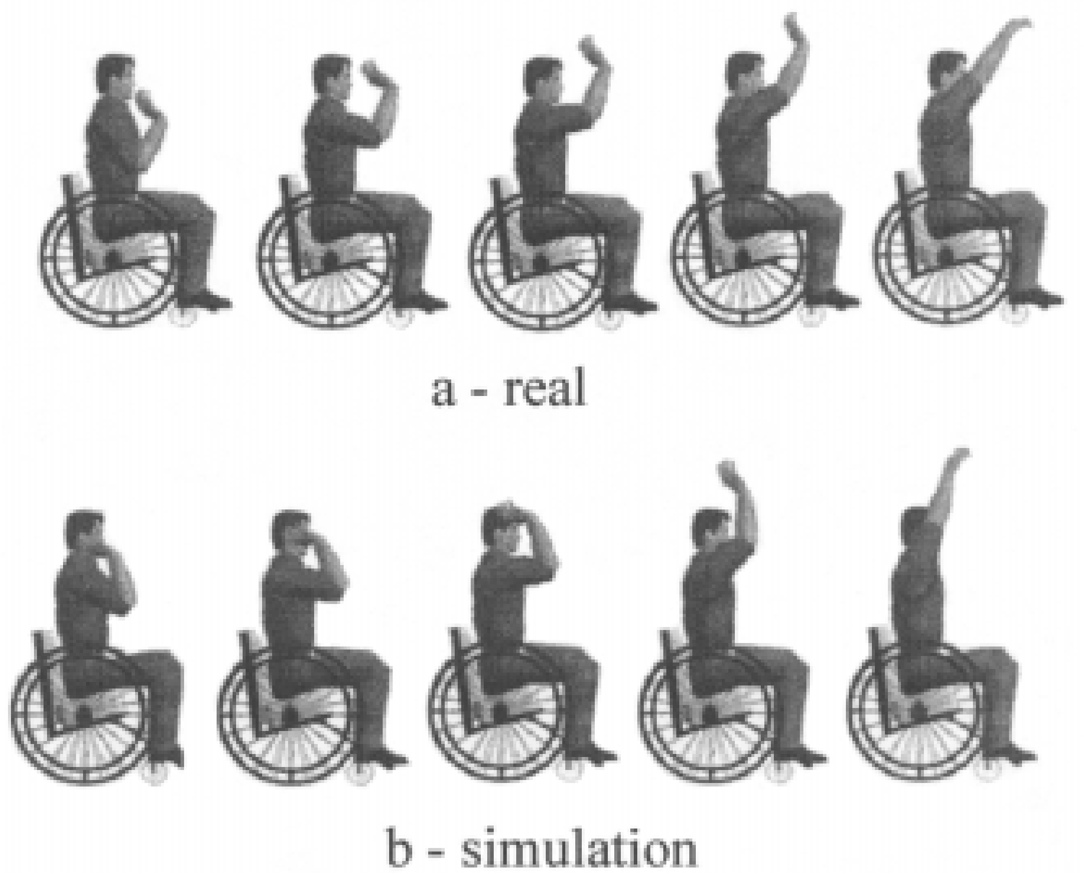

Figure 5 — Comparison of the sequential movement pattern of a real player (a) and that produced by the optimized model (b) starting from the position shown in Fig. 2b.

Discussion

It was found that the optimal speed and angle at release could be determined equally well using either Brancazio's criterion of least speed at release, or Hay's criterion of maximum error tolerance for a ±1° of variation in the angle of release. As such, Brancazio's method makes the most sense to use since the lowest release speed that ends in a successful basket will also correspond to the lowest summation of forces the player will have to produce. This is advantageous because, as has been demonstrated in the area of motor learning, the less muscle torque a player has to generate to accelerate the ball, the more consistent the player should be in replicating the optimal release conditions (Miller & Bartlett, 1996; Sherwood & Schmidt, 1980; Sherwood, Schmidt, & Walter, 1988; Tan & Miller, 1981).

Hamilton and Reinschmidt (1997) took the spin of the ball into consideration in their model and concluded for a standing free throw that the optimal angle and speed of release is greater than predicted by either Brancazio or Hay. For a shot taken at a horizontal distance of 4 m from the center of the basket, and 1 m below the rim (values used by Hamilton & Reinschmidt, 1997), and neglecting air resistance, the magnitude of release speed would be 7.7 m/s for their calculated

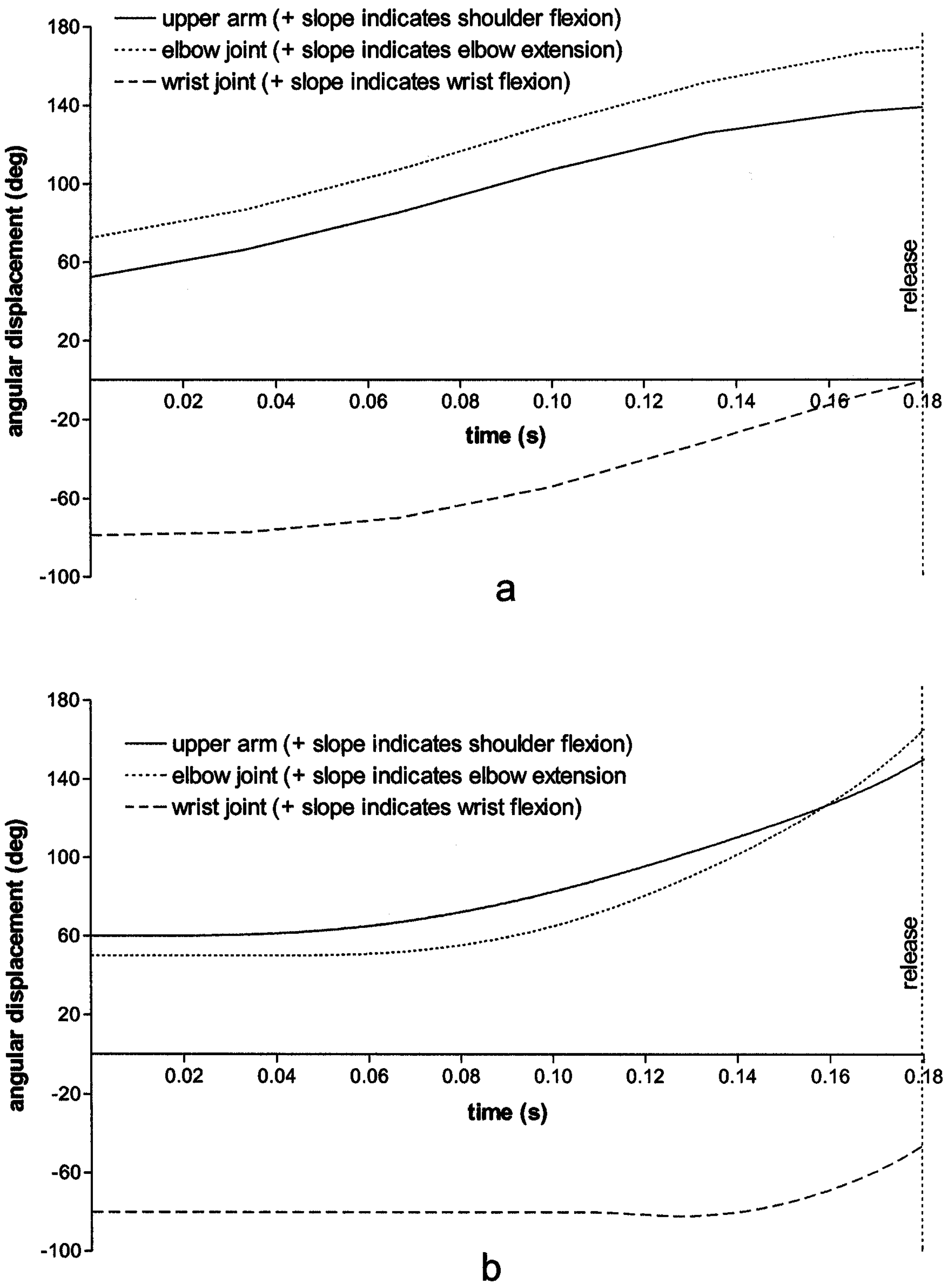

Figure 6 — Angular displacement histories for the real player (a) and the optimized model (b). Upper arm displacement is an absolute measurement with respect to a vertical reference line through the shoulder joint. Elbow and wrist joint angles are relative angular displacement measures. A wrist joint angle of 0° corresponds to the hand and forearm being in a straight line.

optimal release angle of 60°. This speed of release is 0.7 m/s higher than that required for a release angle of 52°, which is the angle predicted by Brancazio's model to be optimum for that same distance from the basket. In their thorough examination of the free throw, Hamilton and Reinschmidt (1997) did not consider, from a player's perspective, the increased difficulty of accurately producing a higher speed of release.

Hubbard, de Mestre, and Scott (2001), in a study that examined the optimal release variables for the shot put, warned against determining the optimal angle of projection without considering the musculoskeletal constraints of the individual athlete. However, the shot put is an example in which maximum effort is required of the athlete, whereas the free throw is a controlled movement that does not require maximum effort. As such, the athlete's performance is not limited by the peak magnitude of impulse he/she can deliver at any given angle of projection. Thus we felt justified in using Brancazio's least speed at release as the best objective function criterion for determining the optimal angle and speed of release. It should also be noted that Brancazio's least release velocity imagery can be a good teaching aid. Explaining to the shooter that minimum release velocity will generally correspond to the shooting technique that takes the least effort to get the ball to the basket should facilitate the learning process. From a player's perspective, attempting to reproduce a given ideal angle of projection is more difficult to execute, especially since the ideal angle of projection depends on the distance from the basket.

Individuals who play basketball from a wheelchair are at a disadvantage in the skill of free-throw shooting, as they must shoot from a lower position compared to a standing player (Owen, 1982). As the height of ball release decreases, the margin for error in release angle also decreases (Brancazio, 1981). The optimization results of the current study indicate that both the release speed and release angle of the ball have to be greater when shooting from a wheelchair. For a wheelchair example in which the ball was released approximately 40 cm below that recorded for a standing free throw, the angle of release increased by 2.5° while the speed of release increased by 0.32 m/s. This additional increase in speed is due to the increase in the vertical component of velocity that must be produced to compensate for the greater vertical distance the ball must travel to the hoop.

In examining, step by step, the instantaneous velocity profile of the ball during the simulation sequence, it was evident that shoulder torque was primarily responsible for producing the vertical component of velocity. At the stages of simulation where the elbow and wrist torques were activated (Figure 3b), the longitudinal axis of the forearm, and to a lesser extent that of the hand segment, were close to vertical, which means that rotation about their respective joint centers would contribute predominantly horizontal velocity to the ball. Because a greater demand is placed on the shoulder actuator during a free throw from the wheelchair, the upper arm tends to finish in a more vertical position than is observed for a typical standing free throw (Figures 5a, 5b).

For a release point 1.1 m above the free-throw line, the optimal release speed was 7.4 m/s and the optimal angle of projection was 53.8°. This is in agreement with the optimal values determined by Malone et al. (2002) for a similar release point from the basket. Malone et al. (2002) reported a mean projection angle of 55° from the free-throw line for 26 shots analyzed for class 4.0 and 4.5 players at the 1994 Gold Cup Tournament. This release angle is close to, but slightly less than, the optimal release angle predicted in both their study and ours.

The simulated wheelchair results revealed that even though the ball had to be projected with a greater vertical component of velocity when sitting in a wheelchair, the vertical speed of the ball as it descended to rim height was 0.39 m/s less than when the ball was projected from a higher release point using a standing position. If slight contact with the rim was to occur, one would expect that this lower impact speed associated with the wheelchair free throw would increase the chance of making a basket.

Malone et al. (2000) reported that the majority of missed free throws in wheelchair basketball fell short of the basket, indicating insufficient force or trajectory to reach the target. This perhaps reflects a number of factors of which arm strength and technique would play a significant role. Wheelchair basketball players classified as 1 or 2 on the IWBF classification system would find it difficult to generate force from the shoulder since their nonstable trunk may not support the reaction forces. For this reason, the results of this study are delimited to wheelchair players classified as 3 to 4.5 on the international player classification system.

In conclusion, we have determined that for any given distance from the basket at release, the two different approaches taken by Brancazio (1981) and Hay (1993) for optimizing the performance of shooting predict the same speed and angle of release. The instructional ease of conveying Brancazio's minimal release velocity to the player makes it a very attractive learning aid for basketball in general. The optimal release speed and angle of projection are greater for the wheelchair free throw than for a free throw taken from the standing position. Free-throw shooting from a wheelchair places more emphasis on a player's ability to generate the increased shoulder flexion torque required by the shot.

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