Optimal mass of the arm segments in throwing: A two-dimensional computer simulation study

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Abstract

Producing a high release speed is important in throwing sports such as baseball and the javelin throw. Athletes in throwing sports might be able to achieve a greater throwing speed by improving the effectiveness of the kinetic chain. In this study a two-dimensional computer simulation model of overarm throwing was used to examine the effect of changes in forearm mass and upper arm mass on the release speed of a lightweight (58 g) projectile. The simulations showed that increasing the mass of the forearm decreases release speed, whereas increasing the mass of the upper arm initially increases release speed. For a given forearm mass there is an optimal upper arm mass that produces the greatest release speed. However, the optimal upper arm mass (5–6 kg) is substantially greater than that of an average adult (2.1 kg). These results suggest that athletes might be able to throw faster if they had a stronger tapering of segment mass along the length of their arm. A stronger taper could be readily achieved by attaching weights to the upper arm or by using hypertrophy training to increase the mass of the upper arm. High-speed overarm throwing is a complex three-dimensional movement and this study was a preliminary investigation into the effect of arm segment mass on throwing performance. Further simulation studies using three-dimensional throwing models are needed to generate more accurate insights, and the predictions of the simulation studies should be compared to data from experimental intervention studies of throwing sports.

Introduction

Humans are able to throw projectiles at high speed and with great accuracy. However, there can be substantial differences in throwing performance among individuals due to differences in muscular strength, body size, and movement skill. Here, we report results from an investigation into the effect of the mass of the arm segments on projectile release speed in overarm throwing. Maximising release speed is important in throwing sports such as baseball and the javelin throw. Our study was inspired by the prospect that athletes in throwing sports might be able to achieve greater throwing speeds by adjusting the mass of their arm segments to improve the effectiveness of the kinetic chain.

It is well known that a person with greater muscular strength tends to throw faster because they produce greater joint torques and joint angular velocities, and a person with longer body segment lengths tends to throw faster because they can accelerate the projectile over a greater path length. Likewise, a person with a more skilful sequencing of actions tends to throw faster because more of the work performed by the joint torques is converted into the kinetic energy of the projectile. Many studies have shown that highly skilled throwers use a proximal-distal sequence, where the peak values in joint torque and joint angular velocity occur later in the joints that are further along the kinetic chain towards the projectile. For example, expert baseball pitching is powered by rapid sequential activation of many muscles, starting in the legs and progressing through the hips, torso, shoulder, elbow, and wrist.[1,2,3] The torques generated at each joint accelerate the segmental masses, creating rapid angular movements that accumulate a high kinetic energy in the projectile at its release. This whip-like coordination is due to the dynamic coupling of the joints, whereby a torque at one joint induces angular acceleration at all joints in the system.[4]

The effectiveness of the whip-like coordination in throwing might be strongly affected by the masses of the arm segments. In most humans the mass of the upper arm segment is about

75% greater than that of the forearm segment.[5,6] This mass difference is believed to enhance the whip-like coordination and help produce a high projectile speed.[7,8] However, there can be substantial inter-individual differences in the mass of a given body segment, and the mass of some segments can be readily changed through muscle hypertrophy exercises.

Unfortunately, we have limited understanding of the effect of the mass of the arm segments on joint sequencing and release speed in overarm throwing. In a study of the movement patterns of young adult males when throwing an underweight baseball, Southard[9] found that hand speed was increased by about 15% when 1.4 kg of lead shot was attached around the upper arm. Although the tapering of mass along of the human arm very likely assists the generation of a high release speed, the results from this study suggests that the mass distribution of many individuals might not be optimal.

Computer simulation can be an effective method of investigating the dynamics of human movement.[10] Previous investigators have used a two-dimensional models of the arm to show that a proximal-distal onset of muscle activation or joint torque leads to the best throwing performance, and this pattern is best irrespective of changes to segment mass and segment length.[11,12,13,14] However, these studies did not explicitly investigate the effect of changing the mass of the arm segments on the release speed of the projectile.

The purpose of the present study was to use a two-dimensional computer simulation model of overarm throwing to examine the effect of changes in forearm mass and upper arm mass on the release speed of a projectile. A straight-forward interpretation of the whip-like coordination in throwing led us to expect release speed to decrease with increasing forearm mass and to increase with increasing upper arm mass. However, there might be an optimal combination of upper arm mass and forearm mass that produces the greatest release speed.

Methods

A two-dimensional model of overarm throwing was created using proprietary computer simulation software. The model is essentially a double pendulum model, similar to those used to investigate the basic mechanics of the golf swing, the soccer kick, swinging a baseball bat, and swinging a tennis racquet.[15,16,17,18] Our throwing model consisted of an upper arm segment, a forearm segment, and a lightweight ball, and the throwing movement was restricted to the sagittal plane (Figure 1). The throwing action was driven by joint torques at the shoulder and elbow, which were obtained experimentally from a participant who performed a throwing motion similar to that in the model.

The participant was a physically active adult male (age, 30 years; height, 1.72 m; mass, 68.0 kg) who was skilled in throwing but did not have advanced expertise in a throwing sport. The throwing task was a maximal-effort overarm throw that was performed in the sagittal plane without substantial trunk movement. The participant was instructed to keep his hips, trunk, and shoulders fixed and to keep his hand and elbow directly above the shoulder throughout the throwing action. This throwing motion was chosen to be as close as possible to the two-dimensional computer simulation model. The experimental part of this study was conducted in accordance with procedures approved by our institutional ethics committee. We informed the participant of the procedures and inherent risks prior to his involvement in the study and we obtained his written informed consent.

The participant sat in a chair and used his dominant arm to throw a tennis ball (0.058 kg) at a target that was 3 m in front of him at about eye level. Eleven reflective markers were placed on the trunk and dominant arm, and two markers were attached on either side of the ball. Before collecting the data the participant was allowed time to warm up by performing sub-maximal throws. The participant then performed 30 maximum-effort throwing trials. Kinematic data were obtained using eight infrared LED motion capture cameras recording at 150 Hz (Motion Analysis, Santa Rosa, CA, USA), and the raw marker position data were filtered using a lowpass Butterworth filter with a cut-off frequency of 6.8 Hz. Ball release speed was calculated from the ball markers using the method proposed by Nathan.[19] The fastest throw with minimal trunk movement was selected for further analysis. The shoulder and elbow joint torques of this throw were calculated using an upper body model created in OpenSim software that consisted of the trunk segment and the right arm.[20,21] A third-order polynomial curve was fitted to the time histories of the joint torques (Figure 2). As expected, the peak torque of the proximal joint (shoulder) for this throw occurred before the peak torque of the distal joint (elbow), and the peak values of the shoulder torque and elbow torque were similar to those measured in previous studies of throwing.

A two-segment model of overarm throwing was created using Working Model 2D software (Design Simulation Technologies, Canton, MI, USA). The throwing model consisted of an upper arm segment, a forearm segment, and a ball (Figure 1). The ball had the same mass and diameter as a tennis ball. The arm segments had a uniform density and the lengths of the segments were equal to those measured for the participant (upper arm, 0.315 m; forearm, 0.342 m). Anthropometric data reported by Winter[8] were used to calculate the segment mass (upper arm, 1.90 kg; forearm, 1.09 kg) and the location of the segment center of mass relative to the proximal end (upper arm, 0.137 m; forearm, 0.147 m). The moment of inertia of the segment about its center of mass, I_{cm}, was calculated using $I_{\mathrm{cm}} = mr_{\text{g-cm}}^2$, where m is the segment mass and $r_{\text{g-cm}}$ is the radius of gyration about the center of mass (upper arm, 0.322L; forearm, 0.303L, where L is the segment length).

The start position of the throw simulations was set to be the same as that used by the participant (shoulder angle = 55° to the horizontal; elbow angle = 55°) (Figure 1). The instant of ball release in the simulated throws was when the elbow angle reached 92° (full elbow extension = 180°), which was the elbow angle used by the participant. A rotational spring (stiffness = 2 N·m/deg) that simulated the passive structures around the shoulder was added at the shoulder joint to keep the joint angles within anatomical limits.[11] The magnitude of the rotational spring stiffness was determined by making the range of motion of the shoulder in the simulated throw similar to that in the experimental throw.

The model produced a broadly realistic simulation of overarm throwing when using segment and torque values equal to those of the participant. The shoulder torque caused the upper arm segment to rotate forwards, with the elbow joint flexing and then extending again. The time of maximum shoulder angular speed occurred well before the time of maximum elbow angular speed, and the time of maximum elbow angular speed occurred at close to the time of ball release. The model produced values of ball release speed, time of ball release, time of maximum shoulder angular speed, time of maximum elbow angular speed, and minimum elbow angle that were within 10% of those measured for the participant. Although the throwing model used here is a simplification of the complex human musculoskeletal system, it appears to broadly represent the throwing action used by the participant. We concluded that the model was likely to reveal the main effects of different combinations of forearm mass, upper arm mass, and shoulder torque on performance in this type of throw.

For the simulated throws, the forearm mass was changed from 0.5 kg to 2 kg in increments of 0.1 kg and the upper arm mass was changed from 0.5 kg to 10 kg in increments of 0.5 kg, resulting in 320 combinations of forearm mass and upper arm mass. For each simulated throw the ball speed at the time when the elbow angle reached 92° was recorded. The times of maximum upper arm angular speed, maximum forearm angular speed, and ball release were also recorded. Five shoulder torque profiles were investigated: 1) experimental shoulder torque profile, 2) shoulder torque increased by 10%, 3) shoulder torque increased by 20%, 4) shoulder torque decreased by 10%, and 5) shoulder torque decreased by 20%. In all, there were 1600 simulated throws.

Results

The mass of the forearm, the mass of the upper arm, and the magnitude of the shoulder torque all had a substantial effect on ball release speed. As expected, a greater shoulder torque produced a faster ball release speed and ball release speed decreased with increasing forearm mass (Figure 3). For an average adult male of 75 kg, increasing the forearm mass by 0.1 kg decreased the ball release speed by about 0.2 m/s (2%). Ball release speed initially increased with increasing upper arm mass but eventually reached a maximum and then decreased slightly. For an average adult male of 75 kg, increasing the upper arm mass by 0.1 kg initially increased the ball release speed by about 0.04 m/s (0.4%). The optimal upper arm mass (5–6 kg) that produced the greatest ball release speed was considerably greater than the upper arm mass of an average adult male (2.1 kg). The form of the relationships between segment mass and release speed were similar for all values of shoulder torque.

The masses of the arm segments had a moderate effect on the timing of the throw. The time of maximum elbow angular speed coincided with the time of ball release for all combinations of forearm mass, upper arm mass, and shoulder torque. For throws with the arm segment masses equal to that of an average adult male, the maximum shoulder angular speed occurred at about 72% of the total throw time. For throws with the optimal upper arm mass, maximum shoulder angular speed was reached substantially later, at about 80% of the total throw time.

Discussion

The results from this study suggest that the mass of the arm segments could have a substantial effect on release speed in overarm throwing. In the simulated throws, increasing the mass of the forearm decreased release speed whereas increasing the mass of the upper arm initially increased release speed. For a given forearm mass there was an optimal upper arm mass that produced the greatest release speed, but our results suggest that this optimal upper arm mass might be substantially greater than that of an average adult male.

The throw simulations in this study are also representative of adult females. A typical adult female of 65 kg has a forearm mass of 0.9 kg and an upper arm mass of 1.6 kg.[5] For females a 40–90 kg range of body mass has corresponding ranges of 0.6–1.2 kg for forearm mass and 1.0–2.3 kg for upper arm mass. That is, the range of forearm mass and upper arm mass used in our throw simulations encompass the range expected for adult females. Although we did not measure a female participant, the shoulder torque and elbow torque profiles used in our simulations are likely to be similar to those of a skilled adult female.

The findings from our simulation study are broadly consistent with the experimental results obtained by Southard.[9] Although Southard used a slightly heavier ball and a different throwing movement, he observed qualitatively similar phenomena to those revealed by our simulation study. In Southard's study, attaching a large weight (1.4 kg) to the upper arm produced a substantial increase in throwing speed (15%), whereas attaching the same weight to the forearm segment produced a slight decrease in throwing speed (2%).

The present study was inspired by the prospect that athletes in throwing sports might be able to improve the effectiveness of the kinetic chain. In a kinetic chain the inertial parameters of the body segments play a crucial role in creating fast and accurate movements. Overarm throwing is among the fastest movements that a human can produce and skilled throwing relies heavily on the effective use of the kinetic chain to transfer energy from one segment to the next to produce a high release speed.[22,23] A throw-like action produces a high speed at the distal end even if the masses of the segments are equal. However, the tapering of body segment mass along the length of the human arm allows even greater energy to be transferred to the projectile. The results of the present study suggest that athletes could throw faster if they had a stronger tapering of segment mass along the length of their arm. Sports throwing activities that could benefit from an increase in release speed include the javelin throw, baseball pitching, shooting at goal in team handball and water polo, and passing by the quarterback in American football.

One method of increasing the mass taper of the arm is to attach small weights around the circumference of the upper arm segment. However, for some throwing sports we suspect that attaching weights to the athlete would be prohibited by the sport governing body. Another method of increasing the mass of the upper arm segment is through hypertrophy training (i.e., 'bodybuilding'). The practice of hypertrophy training for the biceps and triceps muscles is well understood[24]. An intensive three-month period of isolation exercises can increase the girth of the upper arm by 5 cm, which corresponds to an increase in mass of about 0.4 kg[25]. Hypertrophy training of the upper arm is unlikely to be prohibited by a sport governing body.

Limitations and Future Studies: High-speed overarm throwing is a complex three-dimensional movement. The present study was a preliminary investigation of the effect of arm segment mass on throwing speed and so used a simple two-dimensional model of throwing. This model was not expected to generate numerically accurate predictions of the relationships between arm segment mass and performance for high-speed throwing sports.

The simplified two-dimensional throwing movement investigated in the present study is similar to that seen in children at a very early stage of acquiring throwing skill.[2,26] In this early stage the upper arm plays the dominant role in generating a high ball release speed. However, an advanced throwing motion is characterised by an efficient transfer of energy through the whole kinetic chain, which usually includes a run-up or wind-up, thrusting of the legs and hips, trunk rotation and flexion, powerful medial rotation of the humerus, and rapid wrist flexion.[1,2,3] In skilled overarm throwing, internal shoulder rotation is one of the major contributors to ball release speed.[27] Also, the throwing technique used by highly skilled athletes in sports such as baseball, handball, and javelin throw can be closer to a side-arm throw than to an overarm throw.[28] We are acutely aware that the predictions for the simple throwing movement used in the present study might be substantially different to those for an advanced throwing movement.

Our two-dimensional throwing model did not consider the contributions of the wrist joint and hand segment, but this was not expected to be a substantial limitation. The muscle torque at the wrist joint counteracts the interaction torque between the forearm and hand segments, and thus the wrist joint does not contribute much towards ball release speed.[29] Rather, the motion of the wrist joint has a strong influence on the timing of ball release and the release angle, and thus affects the accuracy of the throw.[30]

Our two-dimensional throwing model also did not consider the contributions of elastic energy storage to producing ball release speed, but again this was not expected to be a substantial limitation for the simplified throwing action investigated here. In a throw by a skilled adult male performer only half of the shoulder rotation power generated during the throwing motion is produced by the shoulder's internal rotator muscles; the balance arises from the release of elastic energy stored in the tendons, ligaments, and muscles that cross the shoulder joint.[23] However, the present study examined a simplified throwing action that was not expected to involve considerable use of elastic energy in the shoulder because the movement of the trunk was constrained. Future studies of high-speed throwing performance in sports are likely to use a complex three-dimensional model of throwing, and the mechanisms of elastic energy storage in these models might have a strong influence on the predicted relationship between arm segment mass and the release speed of the projectile.

Another substantial limitation of our study is that we tested only one projectile mass (0.058 kg). A relatively lightweight ball was used to reduce the risk of discomfort or injury to the participant when performing the constrained throwing action. However, different throwing sports use projectiles with substantially different mass (e.g., baseball 0.148 kg; cricket 0.156 kg; softball 0.180 kg, American football 0.415 kg; water polo 0.425 kg; handball 0.450 kg;

javelin 0.600 kg and 0.800 kg). The optimum arm segment masses that maximise the athlete's release speed are likely to depend on the mass of the projectile.

As highlighted previously, high-speed overarm throwing is a complex three-dimensional movement. Therefore, we recommend further computer simulation studies be conducted using three-dimensional models of the human body. Musculoskeletal models of the human body have been developed using software such as SIMM, OpenSim, and MSMS, and used to investigate walking, running, jumping, and lifting. Such software packages can also be used to develop models of throwing. However, issues over the accuracy of the throw simulations might arise due to the very high mobility of the shoulder complex (clavical, scapula, humerus, glenohumeral joint, acromioclavicular joint, and sternoclavicular joint). Accurate experimental data is needed to validate a simulation model[31], but there may be concerns over the accuracy of motion data for the scapula and angular velocity data for the longitudinal rotation of the humerus. A computer simulation study of high-speed throwing using a three-dimensional musculoskeletal model is likely to be more difficult to conduct than a study of simpler movements such as walking.

The results from the present simulation study suggest that experimental studies of throwing might reveal a meaningful effect of arm segment mass on release speed. We recommend experimental intervention studies be conducted using skilled athletes from the most popular throwing sports (baseball, handball, athletics, American football). Systematic investigations of throwing sports could include the effect of attaching different weights to the athlete's arm segments and trunk, the effect of a program of hypertrophy exercises for the athlete's upper arm segment, and the effect of different weight projectiles in a given sports throwing action.

In summary, the study reported here was a preliminary investigation of the influence of segment mass on the kinetic chain in overarm throwing. This aspect of throwing has previously received little attention. The results from the present study indicate that changing the mass of the arm segments might produce meaningful changes in performance in throwing sports. An important finding from this study is that there might be an optimal upper arm mass that maximises the release speed of the projectile. However, the optimal mass might be specific to the type of throw and the mass of the projectile. Further simulation studies using three-dimensional throwing models are needed to generate more accurate insights, and the predictions of the simulation studies should be compared to data from experimental intervention studies of throwing sports.

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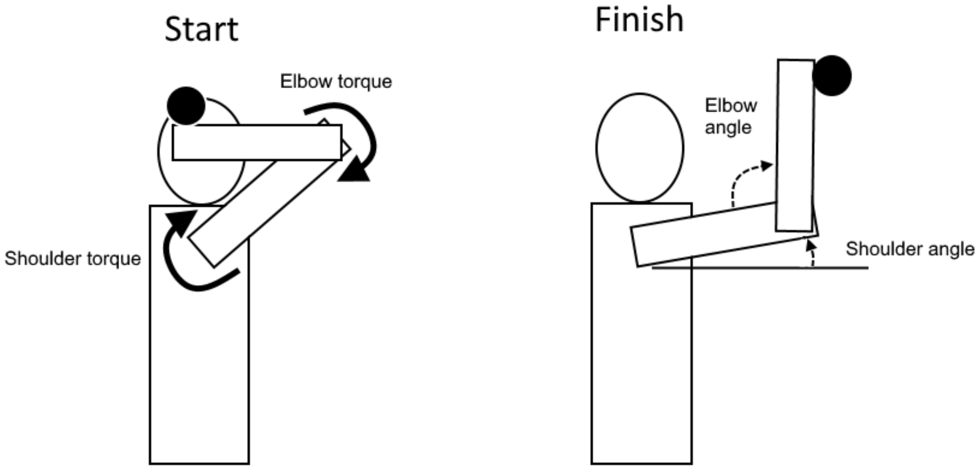


Figure 1. Two-segment model of overarm throwing with two degrees of freedom (shoulder joint and elbow joint). The figure shows the simulation at the start of the throw and at the instant of ball release.

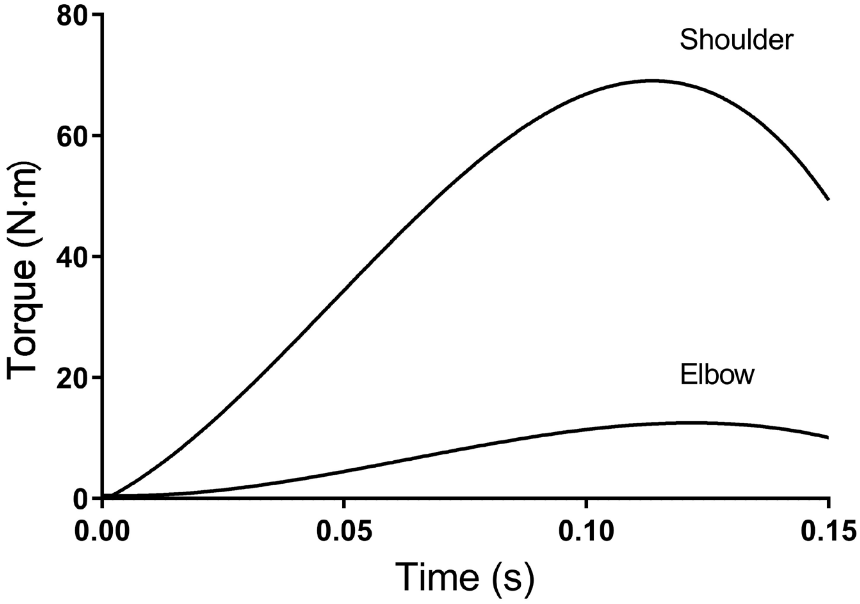
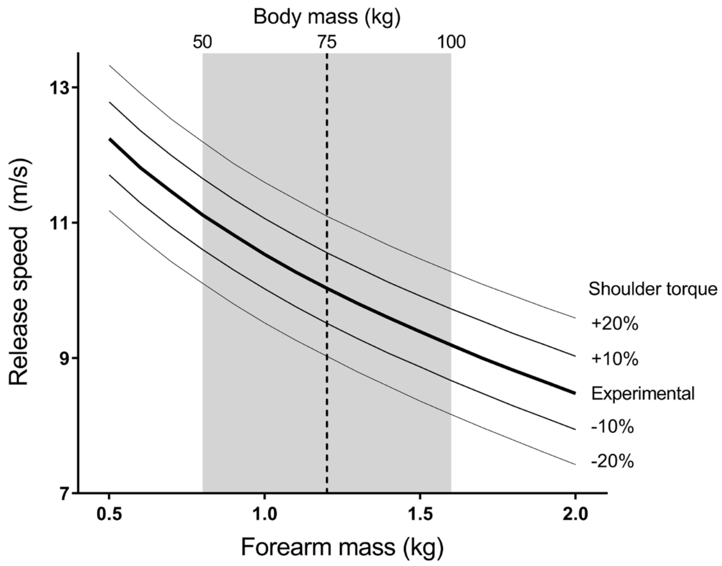
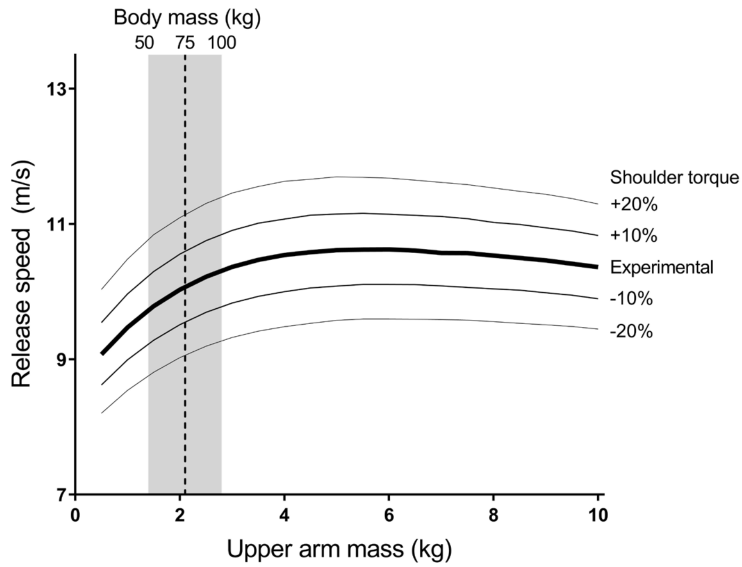


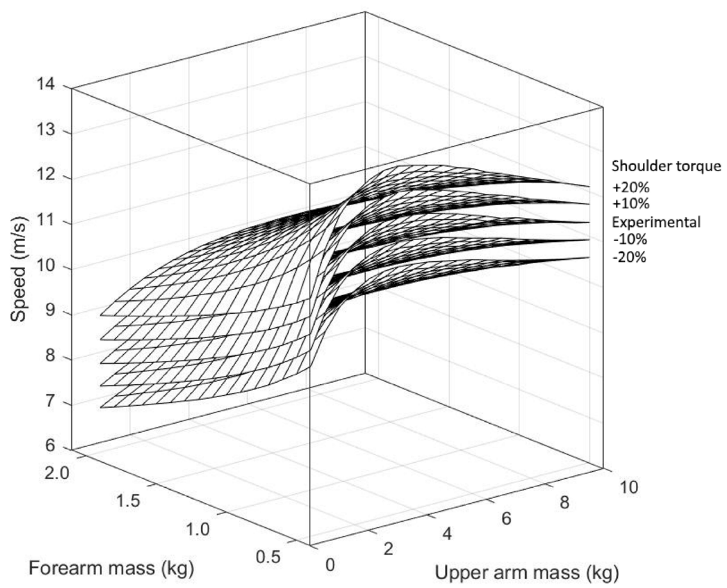
Figure 2. Time trace of the shoulder and elbow torque of the participant.



Body mass (kg)
50
75
100
Release speed (m/s)
13
11
9
7
0.5
1.0
1.5
2.0
Forearm mass (kg)
Shoulder torque
+20%
+10%
Experimental
-10%
-20%



Body mass (kg)
50
75
100
Release speed (m/s)
13
11
9
7
0
2
4
6
8
10
Upper arm mass (kg)
Shoulder torque
+20%
+10%
Experimental
-10%
-20%



Speed (m/s)
14
13
12
11
10
9
8
7
6
Forearm mass (kg)
2.0
1.5
1.0
0.5
Upper arm mass (kg)
0
2
4
6
8
10
Shoulder torque
+20%
+10%
Experimental
-10%
-20%

Figure 3. Effects of forearm mass, upper arm mass, and shoulder torque on ball release speed. (a) Ball release speed decreased with increasing forearm mass. The simulations are for an upper arm mass of 2.0 kg. The shaded area represents the range of forearm mass expected for an adult male weighing between 50 and 100 kg. (b) The optimal upper arm mass that produced the greatest ball release speed was about 5–6 kg. The simulations are for a forearm mass of 1.2 kg. (c) Data from (a) and (b) presented as a 3D plot.