CHAPTER 3

Putting the shot

Our analysis of the path of a projectile has left out an important ingredient, namely, the human element. How does the athlete achieve the maximum initial velocity, height, and the optimum release angle, \( \theta \)? In this chapter we examine shot putting. Grown men and women hurl a heavy round ball as far as they can. Perhaps from the point of view of a fan, not as exciting as a hockey game, but from the scientific point of view quite interesting nonetheless. Since air resistance has a negligible effect on the flight of a shot put (Chapter 1), the mathematical analysis is simplified since we can neglect the effects of air resistance: drag and lift. In fact we can obtain precise predictions in closed form (something that is rarely possible). Thus we have the possibility of directly comparing theory to observation.

In this lecture we ask two questions:

1. What is the best angle to put the shot?
2. What better defines an expert putter; their nervous system or their brawn?

Optimizing \( \theta \)

The major modification we need to make to our analysis in Chapter 2 it that we must account for the fact that the launch point and the landing, or impact, point are not the same (Figure 3.1). Starting with the result we obtained in the preceding chapter

\[
y(t) = x(t) \tan \theta + \frac{g}{2V_0^2} \left( \sec^2 \theta \right) x^2(t)
\]

we take \( x = R \) when \( y = -H \). This yields a quadratic equation in \( R \) and from this the solutions

\[
R = \frac{V_0^2}{g} \sin \theta \cos \theta \left[ 1 \pm \sqrt{1 - \frac{2gH}{V_0^2 \sin^2 \theta}} \right]
\]
Following the same steps as before we can show that for a given launch velocity, $V_0$, maximal range is obtained when the launch angle is

$$\theta_m = \arctan \frac{V_0}{\sqrt{V_0^2 + 2gH}}$$

(3.3)

Note that when $H = 0$ we obtain $\theta = 45^\circ$ which is the same result we had in Chapter 2. The maximum range is

$$R_m = \frac{V_0}{g} \sqrt{V_0^2 + 2gH}$$

(3.4)

In order to apply (3.4) we assume that the origin of the shot put's trajectory is the position of the outstretched hand at the instance of release. For illustration take this position to be 2.29 m above the ground, i.e. $H = -2.29$ m and $V_0 = 13.72$ m/s. Thus we predict that $\theta_m \approx 42^\circ$.

**Experimental observations**

The launch angle for a shot putter has been extensively studied using cinematographic techniques (Bartonietz, 1995; Curelton, 1939; Lanka, 2000). Table 3.1 summarizes measurements obtained from the top male and female finalists in the 1995 World Championships. The release height for these athletes was 2.2-2.3 m. If we assumed that all of these athletes generated $V_0 = 13.72$ m/s, then the distances achieved are actually longer than predicted.

<table>
<thead>
<tr>
<th>Athlete</th>
<th>Launch angle (degrees)</th>
<th>Distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Male</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J. Godina, USA</td>
<td>31</td>
<td>21.47</td>
</tr>
<tr>
<td>M. Halvari, Finland</td>
<td>35</td>
<td>20.93</td>
</tr>
<tr>
<td>R. Barnes, USA</td>
<td>30</td>
<td>20.41</td>
</tr>
<tr>
<td>A. Klimenko, Ukraine</td>
<td>31</td>
<td>18.36</td>
</tr>
<tr>
<td><strong>Female</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S. Storp, Germany</td>
<td>29</td>
<td>18.81</td>
</tr>
<tr>
<td>L. Zhang, China</td>
<td>33</td>
<td>19.07</td>
</tr>
<tr>
<td>V. Fedushina, Ukraine</td>
<td>45</td>
<td>18.03</td>
</tr>
</tbody>
</table>
Human factors in shot putting

Coaches and athletes have observed that height and angle of release are relatively constant for an individual athlete and, from a practical point of view, cannot be changed to improve performance (Dyson, 1968; Grigalku, 1974). Thus increased performance must come from increasing $V_0$. Indeed $V_0$ obviously has an extremely important effect on $R$ since from (3.1)-(3.4) we see that

$$R \sim V_0^2$$

This simple observation raises a number of obvious questions:

1. How much power is required to put the shot over 20 m?
2. How much muscle do we need to generate the required power?
3. What muscles are capable of generating this much power?
4. How is power generated by muscles most efficiently transferred to the shot?

![Figure 3.2: Path length and speed of the shot of an elite shot putter (Lanka, 2000). I, preparatory phase; II, starting phase; III, glide phase; IV, intermediate (transition) phase; V, delivery phase; VI, final phase.](image)

Figure 3.2 shows the path length and speed of a 7.27 kg shot putted 20.11 m in 1974 by the Czechoslovakian shot putter, J. Brabec (Susanka, 1974). Let's estimate the force applied to the shot during the delivery phase (Phase V in
Figure 3.2). If we interpret Newton’s law of acceleration to focus on intervals of time rather than instants of time (we will examine this assumption in more detail in Chapter 5), then this law indicates that the application of an impulse (force times interval time, \( t \)) will result in a change of momentum of the system. Thus the average force, \( \bar{F} \) applied to the shot in Phase V is

\[
\bar{F} = \frac{m(v_f - v_i)}{t} = \frac{m\Delta v}{t}
\]

Estimating the parameters from Figure 3.2 I get

\[
\bar{F} \approx \left( \frac{7.27}{0.236} \right) (15 - 2.5) N = 385.1N
\]

where a Newton (N) is 1 kg-m/s. Do you agree with my estimate?

Now in order to determine power we must first determine how much was done during Phase V of the put. Work, \( W \), is defined as the product of the force times the displacement in the direction of the force, i.e.

\[
W = \int Fdr \approx \bar{F}\Delta r \approx 654.67 \text{ joules}
\]

where out of the cobwebs of our physics 100 course we have remembered that 1 Newton-m = 1 joule.

Power is a measurement of the work done per unit time. Thus the average power, \( \bar{P} \), applied to the shot in Phase V is

\[
\bar{P} = \frac{W}{t} \approx 2774.03 \text{ Watts}
\]

where we remember that 1 Watt is 1 joule/s.

In the English-speaking world we use the unit horsepower (hp) when we discuss power. One horsepower is equal to 746 Watts. Thus we find that in order to move the shot in Phase V requires approximately 3.72 hp!

**Factoid:** One pound of muscle degenerates about 1/8th of a horsepower (Cochran and Stobbs, 1968)

Using our factoid we see that to generate 3.72 hp requires about 29.7 pounds (13.5 kg) of muscle! Where are muscles of this size located on your body? You’re right, you’re sitting on them! So now we are faced with the problem of
how to transfer the power generated in our lower body (note the very polite terminology, hah!) to the shot.

**Evolution of shot putting techniques**

The first clues for understanding how power generated by muscle is applied to a sports projectile by a human athlete comes from studies of the evolution of putting technique. Remember that although athletes are typically not physicists, they are nonetheless continually experimentally with different styles in the hopes that they can get an edge over their fellow competitors.

Over the last one hundred years there have been four variants to the movements used by the athlete to put the shot (Lanka, 2000) (in temporal sequence from old to modern):

1. shot putting from a standing position;
2. shot putting with a glide from the take-off position with one’s side against the push direction;
3. shot putting with a glide from the take-off position with one’s back against the push direction;
4. shot putting with a rotational technique.

It is useful to look at the historical development of putting technique from the perspective of how it utilizes the athlete’s speed and power. During the first stage of technique improvement the push was mainly executed by the hand; during the second and third stages by means of the upper body as well as the hand; during the fourth stage, by including the legs and thereby all the potential sources of the body’s strength and power.

The first relevant innovation after the shot put from a standing position was moving along a circle (glide) followed by a subsequent push off. An athlete started the glide by staying backwards with respect to the movement direction (‘from the side to the push direction’ technique). However, the basis for modern shot putting techniques is due to the inspiration of the US athlete P. O’Brien in the 1950s. He pushed the shot from an initial position with his back against the circle, thus increasing his body’s bendiness and emphasizing rotational movements during the push-off phase.

**Kinetic sequence**

There are two possibilities as to how the power generated by muscles is applied to the shot:

1. $V_0$ is maximized through the temporal coincidence of the trunk and arm movements;
2. $V_0$ is maximized through a sequential activation of body segments:
   typically from proximal to distal, i.e. legs $\rightarrow$ pelvis $\rightarrow$ back $\rightarrow$ shoulders $\rightarrow$
   arm $\rightarrow$ shot.

Cinematographic evidence such as that shown in Figure 3.3 demonstrate that there is not coincidence of muscle activation for shot putting. Clearly, there is a sequential transfer of power from proximal to distal body segments: the legs and hips are the engine, the arms and hands the transmission system. In fact this same kinematic sequence is characteristic when skilled athletes execute all striking and throwing movements; in addition to putting, throwing a ball, discus or javelin, hitting a golf ball.

![Figure 3.3: Resultant speed of main joints (right side of the body) in shot-putting obtained using the motion analysis techniques. Arrows indicate the maximum joint speeds and show that deceleration begins at the knee and proceeds progressively upwards to the hip, shoulder, and wrist (Lanka, 2000).](image)

In general, there are three types of body segment interaction that are possible and these are used depending on the purpose of the movement (Broer, 1960):
1. if the speed of movement is paramount, the actions of segments are consecutive with each segment starting its action at the moment the more proximal segment reaches its maximum speed (kinetic sequence);

2. if the task requires the development of maximum force, all body segments act simultaneously, and it is not efficient to engage weaker segments;

3. if one or more segments are engaged in the activity, the lower segments should be fixed, providing a stable base for a more effective performance by the upper segments.

Figure 3.4: Kinematic sequence for a good golf swing (PGA professional). 1) hips; 2) upper torso; 3) arms; 4) club head. Note that before impact the hips first reach maximal speed, followed in order by upper torso, arms and club. ‘Top’ refers to the top of the back-swing and ‘Impact’ is the instance at which the ball is struck.

Learning the Kinetic Sequence

Despite the paramount importance of the kinematic sequence for elite athletic performance very little is known about how it develops. It is known that the basic building blocks of the kinematic sequences for sports related motor skills, such as throwing, catching, hitting and kicking, are acquired by most children by ages 5-6 (for a useful review see Gabbard, 2000). Qualitatively, the acquisition of these skills seems to go along the line of a progressive refinement of a kinetic sequence.

As an example consider the development of kicking skill shown in Figure 3.5. Four stages in the development of kicking skill have been identified (Deake, 1950): Stage 1: kicking leg is nearly straight and exhibits minimal coordination with rest of body; Stage 2: increased flexion of the kicking leg (pre-contact) and
Figure 3.5: Deach's four stages for the development of kicking behavior (see text for discussion).

some arm opposition; Stage 3: increased preliminary hip extension, greater range of leg motion, and additional body adjustments; and Stage 4: mature form of kicking behavior. Thus there is the progressive refinement into how power generated by the upper part of the leg, pelvis and lower back are transferred to the kicking motion of the foot.
The advanced adjustments to these kinematic sequences required for specific sports, e.g. pitching in baseball, wrist shot in hockey, begin to develop between ages 6-12 (Wickstrom, 1983) and are continually refined by experience and practice throughout adolescence and early adulthood. The acquisition of these motor skills is not hard-wired into the developing nervous system but is driven by the preferences and motivations of the child towards a specific sport and the opportunities provided by the home and school environment. Consequently many never acquire high levels of motor skill. For example, the over arm throwing pattern is a motor skill that has a relatively high incidence of individuals who do not accomplish this skill, especially among females (Halverson, et al., 1982). Another example is the golf swing.

The three most important factors for sports achievement are practice, practice, and more practice. Log-log plots of motor skill versus practice time are linear (Fitts and Posner, 1973): each incremental improvement in skill requires progressively more practice. Thus, a novice typically experiences larger improvement in skill following a focused period of practice than a more skilled performer. These observations are consistent with suggestions that learning is on a ‘trial and error’ basis (Chialvo and Bak, 1999), possibly influenced by mimicry of the movements of more skilled individuals, such as sports heroes.

One mechanism for skill acquisition is repetition. However, by itself, repetition is a very slow and inefficient method to perfect a motor skill. Estimates of the numbers of repetitions to acquire elite levels of performance are in the range of 1-3 x 10^6 repetitions (Fitts and Posner, 1973). Thus, attainment of expert skill levels requires years of practice. There is also a dark side to repetition as a method to refine motor skills. Repetition of stereotyped movements with poor techniques and improperly designed equipment leads to the development of overuse injuries, such as back pain and entrapment neuropathies (Sahrmann, 2002). Consequently, research has begun to focus on the development of new teaching strategies that enable skill to be acquired with less physical practice time and hence less risk of injury.

Three novel concepts have gradually emerged. First variability in practice and problem solving during the early years is more important for the later acquirement of a sports skill than is specific instruction in the sports skill (Carson and Wiegand, 1979; Schmidt, 1988; Yan, et al, 1998). Thus the motor programs that are stored in memory are not specific records of the movements to be preformed, but a set of general rules, concepts, and relationships that can be called upon to solve situations as they arise. These findings have important implications for how practice sessions should be structured.
Second, neuro-psychological studies emphasize that mental rehearsal of skilled movements is at least as important as practice for the development of expertise (Herbert, et al., 1998; Yue and Cole, 1992). Several studies have shown that motor imagery parallels motor planning and execution (Jeannerod, 1994). For example, muscle excitation levels increase during imagery in precisely those muscles that are implicated in the imagined movements (Bakker, et al., 1996; Hale, 1982; Harris and Robinson, 1986). In fact mental imagery alone is sufficient to reproduce all of the autonomic changes, i.e. changes in breathing, heart rate, sweating, that are associated with the physical performance of the activity (Oishi, et al., 2000).

Finally, performance, particularly in stressful game situations, depends critically on the "inner game" (Linden, et al., 2002). Being skilled in a motor task is not the same as being able to perform the task in a game situation (Linden, et al., 2002). At every skill level, performance can be enhanced by teaching programs that include techniques from sports psychology, such as goal setting, positive self-talk, relaxation, and imagery (Lutz, 1999).

**Brain versus brawn?**

The main feature that distinguishes the performance of an elite athlete is that there is a greater and more precise segment interaction than that of the less-skilled athlete (Lanka, 2000). Proper sequencing and timing of body segment interactions arises as a consequence of signals generated by the nervous system. Thus we are led to the surprising conclusion that, all things being equal, the seat of expert performance lies somewhere between the ears of the athlete.

However, before trading off physical conditioning for brain conditioning it is important to keep all of this in perspective. Today’s top shot putters can push a shot from a standing position to a distance of 19-20 m (release velocity of \(\approx 13 \text{ m/s}\)). The current world outdoor record for putting a 13.27 kg shot is 23.12 m (Randy Barnes USA, Los Angeles, May 20, 1990) and the indoor record is 22.66 m (Randy Barnes USA, Los Angeles, Jan. 20, 1989). Thus the contribution of technique over brawn is only of the order of 3-4 m!

**References**


Broer MR (1960). *Efficiency of Human Movement*. (W. B. Saunders,
Philadelphia).


Sahrmann SA (2002). Diagnosis and Treatment of Movement Impairment Syndromes. (Mosby, St. Louis).


HOMEWORK QUESTIONS

Word Questions

1. Which strategy do you think it is better to teach first to your child who wants to be a power slugger in baseball? Learn to hit it as far as possible, then worry about technique; or teach proper technique first and then get them to hit it further?

Math Questions

2. Complete Table 3.1 by using (3.4).

3. Given the measured launch angles for the different shot putters in Table 3.1, what initial velocity must have been generated by each of them to achieve the measured distance?

Golden Beanie Question

None this week!