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Reassessing Velocity Generation in Hammer Throwing

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By Andreas V. Maheras

ABSTRACT

In the hammer throw, the exertion of the force necessary to increase the horizontal velocity of the implement is thought to take place mainly when both the thrower's feet are in contact with the ground during the double-support phases of the turns. Coaches have therefore sought to maximise the duration and the effectiveness of the double-support phases while minimising the length of the single-support phases, when it is assumed that the thrower is preparing for the next double-support. However, as scientific understanding of the event has developed things have become less clear. It is now known that the horizontal velocity of the hammer is increased mainly in the winds or early part of the throw, when the thrower is stationary or rotating slowly, and that the observed increase in velocity during the turns is due not to a horizontal pull-push of the feet against the ground but to the addition of vertical velocity and a shortening of the hammer radius. Therefore, emphasis on the double-support phases may well be misplaced. Stressing that there is still much that is not known about the hammer throw, the author explains current understanding of the event in detail and makes recommendations for coaches to consider.

AUTHOR

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Introduction

The hammer throw movement starts with the execution of two or three winds, which are followed by three or four turns, in which the thrower rotates with the hammer in a synchronised fashion. During the winds and subsequent turns, the velocity of the hammer increases progressively until the moment of release following the last turn. The velocity of the hammer at release is a determining factor for the length of the throw. As the throwing movement progresses, three important features can be observed: 1) the circular motion of the hammer around the thrower, 2) the gradual change of the slope of the hammer's plane of movement, and 3) the horizontal translation of the thrower-plus-hammer system across the circle.

In the early part of the throw, the hammer's plane of movement is rather flat but it becomes steeper as the throw advances and it reaches a slope of approximately 40°

during the last turn. The thrower keeps the hammer on its circular path by exerting a centripetal force, which can be over 300kg during the last turn of a world record throw, through the wire to the centre of the ball. In turn, the wire exerts an equal and opposite force on the hands of the thrower, which tends to pull him/her forward (DAPENA, 1989).

The concept of hammer throw technique held by most coaches has long included the following two elements. First, the winds at the beginning of the throw have been seen as a preliminary movement with a much less important impact on the velocity of the hammer than the turns that follow. Consequently, relatively little attention has been paid to this element of the overall movement. Second, it has been thought that exertion of the force necessary to increase the horizontal velocity of the hammer mainly takes place when the thrower's feet are both in contact with the ground during the double-support phases of the turns. Coaches have therefore sought to maximise the duration and effectiveness of the double-support phases while minimising the single-support phases, when it is assumed that the thrower is in a recovery phase preparing for the next double-support.

However, as scientific understanding of the event has developed, the situation has become less clear. For a start, there is still much that we do not know. What we can see now is that the winds are the thrower's best opportunity to increase horizontal velocity and that vertical velocity is a very important component of the hammer's total velocity. We can also see that emphasis on the double-support phases may well be misplaced. This is not to say the double-support is unimportant, but there are certainly other aspects to increasing the velocity of the hammer at release that must be considered. In this article I will explain these statements in detail and make recommendations for coaches to take into account when thinking about hammer throw technique.

Hammer Throw vs. Tug-of-War

As the thrower-plus-hammer system advances across the circle, one may think that the thrower uses forces resulting from the friction between his/her feet and the ground to resist against being pulled forward, much like what happens in tug-of-war (WOICIK, 1980). However, the dynamics of the two activities are quite different. In hammer throwing, the reactionary forces that keep the hammer ball on its circular path, also serve to keep the thrower on his/her own, circular path. This implies that the thrower does not push forward on the ground in order to stay in place.

Figure 1 shows what happens in what could be called a tug-of-war scenario (DAPENA, 2007). Here, F1 is the forward force made by the wire on the hands; F2 is the weight; F3 is the vertical force made by the ground on the foot; F4 is the horizontal force made by the ground on the foot. F2 is about the same size as F3, so they essentially cancel each other out; F1 is about the same size as F4, so they also cancel out. The sum of all the forces made on the thrower is approximately zero and he/she not moving at all (in a static condition). In other words, the body of the thrower experiences no linear acceleration.

Figure 2, shows what really happens in hammer throwing. Here, force F4 is essentially missing. So forces F2 and F3 essentially cancel each other out, leaving us with force F1, which, indeed, accelerates the body forward. But this forward acceleration will not make the thrower actually translate forward and fall flat on his/her face. The reason is that the thrower (like the hammer) is rotating about the combined centre of mass (CM) of the thrower-plus-hammer system. In Figure 3 we see that the thrower's CM (yellow dot) is very close to the combined system CM (green dot), so the radius of the path (violet line) followed by the thrower's CM about the combined system CM is pretty small, the distance between those two dots. But the thrower's CM is indeed rotating about the combined system CM, and such a rotation (like any

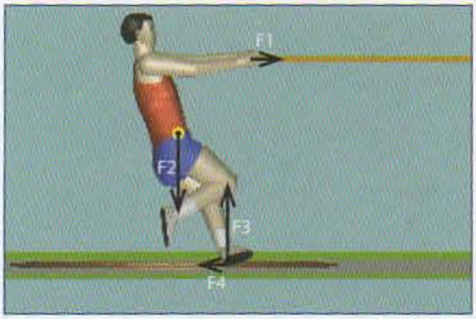

Figure 1: Forces on the athlete in a tug-of-war (adapted from: DAPENA, 2007, reprinted by permission)

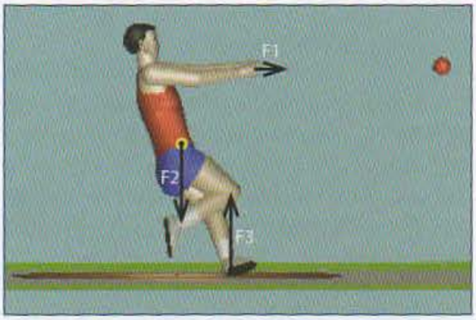

Figure 2: Forces on the thrower in hammer throwing (adapted from: DAPENA, 2007, reprinted by permission)

other rotation) requires a centripetal acceleration, a force to keep the body's CM following that short-radius circular path. And that force is exerted by the hammer on the hands through the wire, which we have called F1 in Figures 1, 2 and 3.

In the same way, the reaction to F1 is the force exerted by the hands on the hammer ball through the wire, and this reaction force (which we could call force F5 for example, but it is not drawn in the figures), is the centripetal force that keeps the hammer ball rotating about the combined system CM (the hammer's orange path).

The phenomenon described shows that some of the forces required to maintain the static balance of the tug-of-war athlete are not necessary for the dynamic balance of the

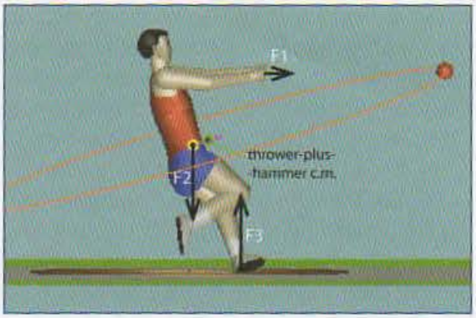

Figure 3: The combined centre of mass of the thrower-plus-hammer system (adapted from: DAPENA, 2007, reprinted by permission)

rotating hammer thrower. It also shows the need for coaches to make a distinction between static and dynamic balance when dealing with hammer throwing.

The "Long Double-Support" Model

However, simply keeping the hammer on a circular path will not suffice. The thrower also needs to increase the velocity of the hammer. According to some authors (BONDARCHUK, 1977; BLACK 3, 1980; WOICIK, 1980) hammer velocity can generally be increased most effectively during the double-support phases of the throw and DAPENA (1984) has observed that hammer velocity increases between the high and low points of its orbit, which roughly coincide with the beginning and the end of the double-support phase respectively. Therefore, it seems logical to assume that it is easier to produce a rotation about the vertical axis when both feet are in contact with the ground than when only one foot is in contact with the ground. It also seems logical to assume that the single-support phase is a recovery phase during which the athlete prepares for another double-support phase.

It follows, therefore, that maximising the double-support phase and minimising the single-support phase is a prudent way to go about increasing force output in hammer throwing. One action that has been used to achieve this aim involves keeping the right leg close to the body. This enables the thrower to speed up during single-support and thus to plant his/her right foot sooner to start the next double-support. Another movement involves the landing of the right foot with the toe pointing towards the 270° azimuthal angle instead of the 0° angle. This will also allow the thrower to plant the right foot earlier, again shortening the single-support phase and lengthening the double-support phase. The thinking behind both these movements is based on the simple model:

- double-support = when the thrower can increase hammer velocity,
- single-support = a waiting period.

However, just because two quantities coincide in time does not mean that one causes the other. In fact, no direct cause and effect link has been shown between the double-support phase and the increase in hammer velocity (DAPENA, 1989). Moreover, film analysis data may not fully support the theory either (GUTIERREZ, SOTO & ROJAS, 2002). It is possible then that the association between hammer velocity increase and the double-support is spurious and coincidental and, importantly, that there may be other factors involved.

One such a factor may be gravity. As the hammer moves upwards and downwards in its sloped plane of movement, gravity naturally will affect its velocity.

Another factor may be the horizontal translation of the thrower-plus-hammer system. We can see this in Figure 4 (a), where we assume an item is attached at the edge of the circular table rotating anticlockwise around itself (vertical axis) and that the linear velocity of the attached item is a constant 26 m/s. Subsequently, if we push the table horizontally at a constant velocity of 2 m/s, as shown in Figure 4 (b), the instantaneous velocity of the item itself will be 28 m/s relative to the ground (26+2) when the item reaches the 90° azimuthal angle, because the item is moving in the same direction as the system's CM, and 24 m/s relative to the ground (26 – 2) when the item reaches the 270° azimuthal angle, because the item and the system's CM are

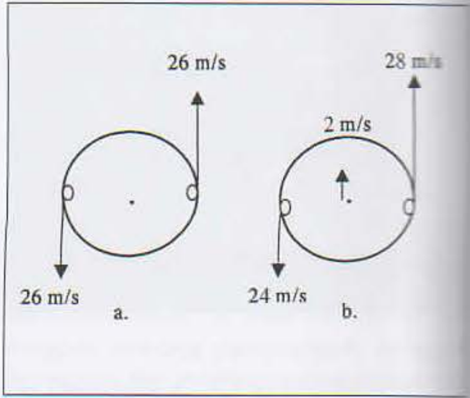

Figure 4: Relative velocity of an item rotating around a circular path (a) without and (b) with horizontal translation

now moving in opposite directions. The velocity then will fluctuate between 24 and 28 m/s throughout the turns because there is a combination of rotation at a constant angular velocity and forward translation at a constant linear velocity.

A similar phenomenon may occur during hammer throwing, with the hammer ball being the item rotating in a circular path while simultaneously there is a horizontal translation of the thrower-plus-hammer system across the circle. Such a combined movement will affect the velocity of the hammer.

These two factors, gravity and horizontal translation, can be mathematically accounted for and subsequently removed from consideration when the hammer velocity is calculated (DAPENA, 1984). Under these circumstances, in some throwers, the fluctuations observed in the velocity of the hammer disappeared. Yet in others, there was still indication of this fluctuation. Thus, it is possible that other factors may also be affecting hammer velocity in some throwers.

Horizontal and Vertical Velocity Generation

Another problem with the "long double-support" hypothesis is that it only considers rotation about the vertical axis. This implies

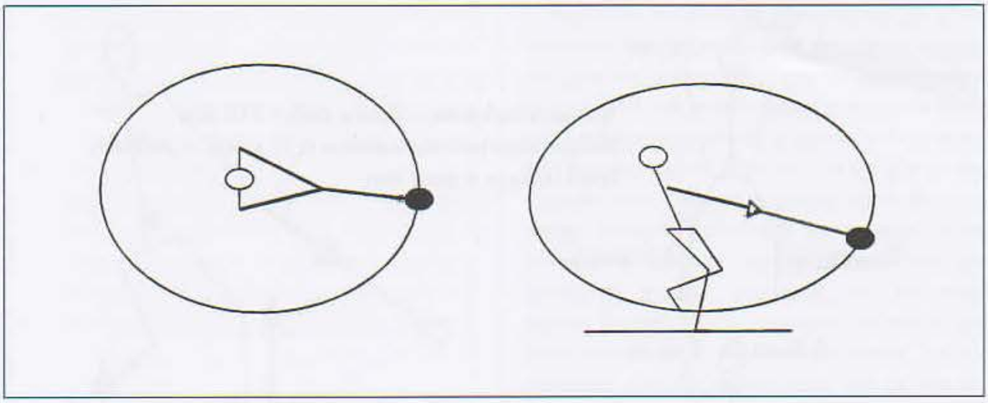

Figure 5: Rotation about a vertical axis (left), view from overhead, and rotation about a horizontal axis (right), view from the 00 azimuthal direction-front

that the motion of the hammer ball is only on a horizontal plane (WOICIK, 1980). In reality, however, the motion of the hammer also takes place about the horizontal axis, which implies motion of the ball on a vertical plane (Figure 5). It is clear then, that to increase the velocity of the hammer, a thrower needs to obtain a torque not only about the vertical axis, but also about the horizontal axis.

What makes this last statement even more important is the observation that the majority of the increase in velocity during the turns is associated with generation of torque about the horizontal axis. In other words, the majority of velocity increase during the turns is vertical velocity and only a small part of the increase is horizontal velocity (DAPENA, 1989; MUROFUSHI et al., 2007).

It is true that the horizontal velocity of the hammer can be increased much more effectively during double-support than during single-support. However, this is only the case when the thrower is rotating very slowly. When the thrower is rotating fast, it is impossible to increase horizontal velocity in either of the support phases (DAPENA, 1989). Instead of thinking that double-support = good, because only in double-support can a thrower exert torque and, single-support = bad, because in single-support a thrower cannot exert any torque, one may need to modify this thinking accordingly (DAPENA, 2007).

The "big picture" of what happens in hammer throwing, is that during the winds (when the speed of rotation is slow and the thrower is all the time in double-support), the thrower increases the horizontal velocity of the hammer. But by the time the turns start, the hammer is turning fairly fast (just for reference here, at 15 m/s), and the body of the thrower is also turning pretty fast. As a result, during the turns, no more horizontal velocity of the hammer can be generated, regardless of whether it is at an instant in which the thrower is in single-support or at an instant in which he/she is in double-support. If, for the sake of argument, the thrower were forbidden to produce any vertical velocity, the velocity of the hammer at release would be 15 m/s, the same as the velocity of the hammer at the start of the first turn.

But the thrower is not forbidden to generate vertical velocity. Let's say, for example, that during the turns the thrower generates 14 m/s of vertical velocity. This would be the vertical velocity at the steepest point of the path, and it would increase gradually from one turn to the next; for example, from 0 m/s to 4 m/s to 8 m/s to 11 m/s to 14 m/s in the four succes-

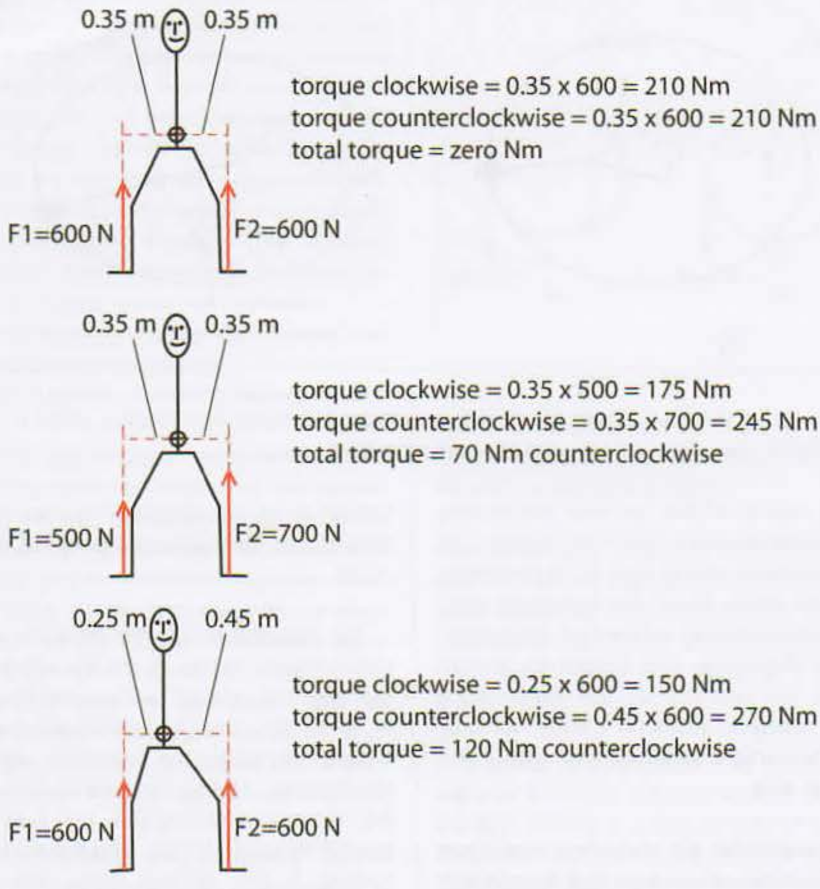

Figure 6: Torque generation during double-support (adapted from: DAPENA, 2007, reprinted by permission) Note: The terms "torque clockwise" and "torque anticlockwise" refer to those directions from the reader's point of view not the thrower's point of view. Therefore, a "clockwise torque" refers to a tendency for a rotation towards the thrower's own left and "anticlockwise torque" refers to a tendency for a rotation towards the thrower's own right.

sive turns. At the end of the last turn the hammer would have this 14 m/s of vertical velocity plus the 15 m/s of horizontal velocity already mentioned. The total velocity would be equal to the square root of ($15^2 + 14^2$), or 20.5 m/s.

What we see in this example is that the hammer did indeed gain velocity during the turns but it did not gain any horizontal velocity, all the gain was in the vertical. Importantly, this gain of vertical velocity had nothing to do with the thrower being in double-support or in single-support. Whether the thrower is in single or double-support matters only in relation to gains of horizontal velocity, and then it would apply only when the horizontal velocity was not yet very high (i.e., during the winds, not during the turns). In other words, the gains in total velocity that occur during the turns are linked to changes in the vertical velocity, which can be produced when the thrower is in double-support or in single-support.

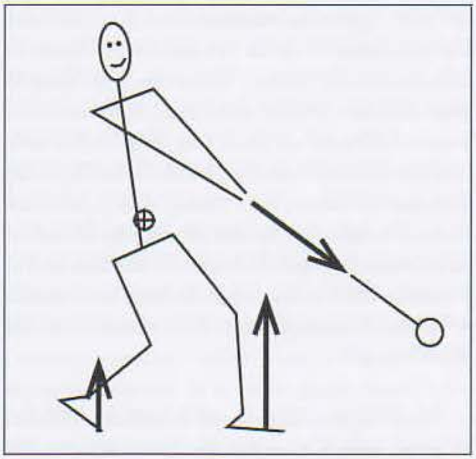

Figure 7. Forces exerted by the feet on the ground and reactionary force exerted on the hands by the cable during double-support (adapted from: DAPENA, 2008, reprinted by permission)

According to DAPENA (1989 and 2008), the torque in the vertical direction (about the horizontal axis) is generated during double-support as follows: first, the thrower presses harder on the ground with the left foot than with the right foot and/or second, the thrower generates vertical forces on the ground with both feet, but keeps the CM of the thrower-hammer system closer to the right foot than to the left foot, instead of half-way between them.

In Figure 6 on top, when the CM is half way between the right and left leg and both feet exert the same forces on the ground, the amount of torque produced in the anticlockwise or the clockwise direction is the same and therefore the total amount of torque produced equals zero. In the middle of Figure 6, the CM is still halfway between the two legs but the left foot exerts a larger torque and the net effect, the difference between the two directions, is a total torque pointing clockwise, from the thrower's point of view, which effectively tends to cause the thrower to rotate in that direction (towards his/her right). From this position if the thrower accidentally let go of the hammer, he/she would fall towards his/her right side.

However, the thrower does not let go of the hammer and by pulling on the cable, he/she will give the hammer an upward acceleration. In turn, the cable will make a reaction force on the thrower's hands (Figure 7). This reaction force will exert a clockwise torque on the thrower and it would normally make him/her rotate toward his/her left (or forward if the thrower is already facing toward the 90° azimuthal angle). However, as discussed earlier, the forces on the feet are such that they produce a net anticlockwise torque (towards the thrower's right) about his/her CM and the clockwise torque exerted by the hammer on the hands about his/her CM (towards the thrower's left) simply cancels out the anticlockwise torque exerted through the feet. The thrower manages to give the hammer an upward acceleration without losing balance, because the total torque on him/her will be zero.

The eventual practical benefit of the left foot pressing harder on the ground is that the thrower will be able to pull harder upward on the hammer during the upward part of the hammer trajectory resulting in an even greater upward acceleration due to that pulling. On the other hand, if the thrower were to press harder with the right foot (instead of the left as we have discussed so far), this would result in a tendency for the thrower to rotate to the left, and the reaction cable force (which also makes the thrower rotate to the left) will add to the forces made on the feet and the thrower will lose balance and fall to the left.

A detail that needs to be mentioned here is that, during most of the time when the hammer ball is travelling upward, the athlete will be not in double-support but in single-support. The uphill motion will occur approximately between the 0° and 180° azimuthal positions of the hammer. During this ascent, the thrower will be in double-support from azimuthal angle of 0° of the hammer to azimuthal angle of 50° or so (very rough value), and from there all the way to 180° he/she will be in single-support. In other words, during most of the uphill travel of the

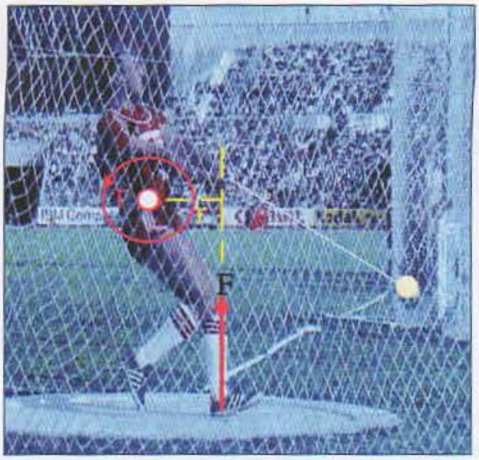

Figure 8: Vertical force (F) made by the ground, and anticlockwise torque (T) produced around the longitudinal Y-axis during single-support (adapted from: DAPENA, 2008, reprinted by permission) Note: This axis would be perpendicular to the page and is passing through the centre of mass (white dot at the right hip area). The torque about the centre of mass would be the product of (r) x (F), and the torque itself would be as indicated by the curved red arrow. The torque vector would be pointing along the Y-axis, from the page toward the reader.

hammer the thrower will be in single-support. Finally, at the bottom of Figure 6, the combination of the location of the CM, which is now more towards the right foot, and the amount of torque generated by the feet, produce an even greater net anticlockwise torque.

During single-support, the torque is produced automatically because the point of support, which is the left foot, is not directly under the thrower, and the reactionary vertical force generated by the ground on the left foot exerts a torque about a longitudinal axis passing through the CM (Figure 8). To better imagine this effect, we can picture someone standing with both feet on the ground. If they were to remove the right foot without making any other changes they would fall toward the right. However, this is not the case during hammer throwing because the torque that the thrower receives from the ground is transmitted to the hammer. This way, the thrower does not fall, despite the fact that the point of support (the left foot) is not directly beneath his/her CM while at the same time the hammer accelerates. We need to point out here that although the existence of the torque is automatic, the size of it can be altered by the thrower, depending on how he/she interacts with the hammer, how he/she uses his/her leg muscles, etc.

Yet another point to add here is that the thrower can (and normally does) reduce the radius of rotation of the hammer ball somewhat as the throw progresses from turn one to turn four. This will produce some increase in the total velocity of the hammer ball. In the example we have been using the total velocity of the ball at the end of the last turn won't be 20.5 m/s, but closer to 24 m/s.

Conclusions

Coaches implicitly tend to think in terms of "distance of force application" to increase horizontal velocity and that force application can only occur in double-support. However, it is an over-simplification to consider that in hammer throwing there is rotation about a vertical axis only. The rotation occurs about an inclined axis, which implies rotation about both a vertical, and a horizontal axis. The rotation about the vertical axis (horizontal velocity) can best be produced during the double-support phase, but only if the thrower is rotating slowly. The rotation about the horizontal axis (vertical velocity) can be produced both during the single-support and double-support phases and thus, single-support phase does not have to be a "recovery" phase.

If we were to assume that the forces generated in hammer throwing (dynamic balance) are similar to those observed in tug-of-war (static balance), then in the double-support phase in hammer throwing it would be possible to push forward on the ground with the left foot and pull backward with the right foot. As a result there would be an increase of the angular momentum of the combined thrower-plus-hammer system about the vertical axis. From this, one could further infer that in single-support it would be much more difficult to increase the angular momentum. Therefore, under those conditions, to generate the maximum possible amount of angular momentum about the vertical axis during the throw, a thrower would want to maximise the time in double-support within each turn. As explained earlier, to do this, there would be a need to minimise the time in single-support. This means that the thrower would want to take off late (for example at the 90° azimuthal angle) and land early (for example at the 220° or 230° azimuthal angle).

However, in reality, the forces generated in hammer throwing are not similar to those of a tug-of-war and the "long double-support" model places the emphasis on the wrong concept. The reason can be found in the sentence in the previous paragraph where it says: "to generate the maximum possible amount of angular momentum about the vertical axis during the throw, a thrower would want to ...". It turns out that generating the maximum possible amount of angular momentum about the vertical axis is NOT the main goal of the hammer thrower (DAPENA, 2008).

Why? Because during the turns the thrower is turning so fast already that it is nearly impossible to push forward on the ground with the left foot and pull backward with the right. Therefore the angular momentum about the vertical axis increases very little. Putting the emphasis on this is focusing on something that is going to be of a small value no matter what. Of course, the actual value of angular momentum about the vertical axis will be big even if the gain during the turns will be small. But this momentum will have been generated, almost all of it, during the winds, with very little of it being generated during the turns. So the most important thing that is happening during the turns is not the change in the angular momentum about the vertical axis, it is the change in the angular momentum about the Y-axis, which is the axis aligned with the midline of the throwing sector and, in turn, this is linked to the changes in the vertical velocity of the hammer.

Following the discussion above, hammer throwers cannot afford to take it easy in the preliminary phase (the winds). They need to produce a lot of hammer velocity already in the winds. Of course, they have to stay under control, but they still need to be very dynamic. Moreover, although the "flatness" of the plane of the winds has been addressed before (e.g. EBERHARD, 1990) it needs to be emphasised that, from a mechanical point of view, throwers need to keep the hammer ball on as flat a path as possible. There will be time later (during the turns) to add vertical velocity but only a small amount of horizontal velocity can be added in the turns so it must be the focus during the winds.

To be clear, we are not saying that a thrower cannot increase hammer velocity in double-support. What we are saying is that a thrower can increase hammer velocity BOTH in double-support and in single-support. What has been observed is that the increase in the velocity of the hammer ball during the turns is due mainly to the addition of vertical velocity, and in part also to the shortening of the hammer radius. But the increase is not due to a horizontal pull-push mechanism of the feet against the ground; that was something that stopped happening with the end of the winds. Moreover, neither the increase of vertical velocity nor the shortening of the hammer ball radius are favoured by being in double-support. That is why, from this point of view, the achievement of a long double-support during the turns may not be as important as many think.

If maximising double-support may not be the best approach in hammer throwing, then what would the alternative be? The answer is we don't know (at least experimentally) the optimal pattern in regard to double-support versus single-support. In the final turn of a hammer throw, it is possible that the thrower does not increase the hammer velocity much during the downward part of the hammer's path (from, say, the 240° azimuthal angle to the 0° azimuthal angle), and that the only hammer velocity increase occurs between the 0° azimuthal angle and release (at the azimuthal angle of 70° or 90° or something like that). In such case, earlier landing of the right foot would not contribute to an increase of the hammer velocity. However, we cannot be sure about this part because here we may be getting near the limits of applicability of the theories and data to actual throwing, but it is perfectly possible.

Again, with all this, we are not trying to denigrate the double-support. We are just trying to say that the single-support is not necessarily the "poor relative" and therefore, it is not the guaranteed wasteland that we used to think. In other words, we cannot be sure anymore that maximising the double-support time is the optimum. Maybe maximising double-support is still the optimum. Or maybe maximising single-support is the optimum. Or maybe some intermediate between the two is the optimum. We simply don't know.

Recommendations

Based on the discussion above, I can make the following recommendations to coaches:

1. During the winds (which are all in double-support), the thrower can increase both horizontal velocity and vertical velocity but for maximum effectiveness needs to concentrate on increasing horizontal velocity during this period.
2. During the single-support phases of the turns, the thrower can increase vertical velocity, and he/she needs to do so.
3. During the double-support phases of the turns, the thrower can also increase vertical velocity and he/she needs to do so.

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