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Investigating the relationship between swing weight and swing speed across different sports using historical data

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Abstract

In many sports, the maximum swing speed of a racket, club or bat is a key performance parameter. Previous research has suggested that a logarithmic relationship exists between the resultant swing speed and the swing weight/moment of inertia of the implement. However, these studies have only focussed on one specific sport and relatively little is known about the effect of swing weight on swing speed across the wider spectrum of sport. Data was collated on the swing speeds achieved in numerous sports that employ an implement and a swinging motion. A range of typical swing weights were determined for the various implements and the data normalised to common conventions such that comparisons could be made. This meta-analysis established a new relationship between swing weight and swing acceleration, valid across the wide range of implements considered. This relationship was found to be of the form $a=C/I^m$, where C is a player constant and m=0.59 ($p<0.01$).

Keywords: Meta-analysis; moment of inertia; swing acceleration; swing speed; swing weight

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1. Introduction

When considering the physics of sporting implements, a key area of consideration is how the physical properties of an implement will affect the performance. Therefore, understanding this relationship is of great importance in order to provide athletes with useful performance information. There are a limited number of physical properties which could be altered to improve performance and within a single sport; restrictions on an implement's mass, length and shape can be set by the sport's governing body. For example, in tennis, the International Tennis Federation state that a racket can have maximal dimensions of

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73.7cm in length, 31.7cm in head width and can have a maximal hitting area of 39.4cm long and 29.2 cm wide [1]. One physical property which is of particular importance is swing weight. Swing weight is a common term referring to the implement's resistance to rotational acceleration and is also known as the moment of inertia. Performance is often measured as the outbound velocity of the impacted object [2]. However, the maximum speed at which the implement can be swung directly influences the outbound object velocity and can therefore also be treated as a key performance parameter.

The concept of swing weight influencing the performance of a sporting implement was first discussed by Daish in 1972 [3] where an experiment was carried out measuring the club head speed for golf drivers with varying club head mass. Daish found there was a linear logarithmic relationship between swing speed and club head mass, however only four players were tested. In 2003 Smith et al. [4] found a similar relationship in softball with an experiment that varied swing weight and mass separately in a series of bats and measured the swing speed. It was found that the mass of a softball bat is almost independent of the swing speed whereas the moment of inertia has a linear relationship with the normalised swing speed for each player in the experiment. A further study was completed by Cross and Bower in 2006 [5] who measured the maximum swing speed achieved with restricted motion when swinging rods with different properties. Cross and Bower converted Daish's club head mass data to show the relationship between moment of inertia and swing speed for the golf clubs. It was found that Daish's data and their own new data could be described by equation 1,

$$V = \frac{C}{I^n} \tag{1}$$

where C is a player constant and n is the gradient of the swing speed - swing weight log plot. This relationship is the same as in the work by Smith et al. and the three studies found the value of n to be 0.26 ±1. A similar study by Crisco et al [6], analysed by Nathan [7], compared angular velocity with moment of inertia in baseball and found $n=0.28 \pm 0.04$, which is very comparable to Daish, Smith et al and Cross and Bower's work, which suggests a relationship may exist between different sports as well as within a single activity.

The research in the literature is very much focussed on the relationships present in a single sport and very little work has been done describing the relationship between swing weight and swing speed across multiple sports. The aim of this work is to review the mechanics of multiple swinging sports and to define the relationship that exists between the moment of inertia and the swing speed across this range of sports.

2. Methods

In order to compare the swing weight and swing speed relationships across several sports an analysis was carried out using data from existing literature. Published data was analysed for nine different sports as listed in Table 1. In the case of tenpin bowling, the 'implement' was defined as being the bowler's arm and ball as one fixed unit which rotates around the shoulder joint. The moment of inertia data for bowling was created using mean body segment data as presented by de Leva [8]. Specific shots chosen were the badminton smash; front foot drive in cricket; field hockey hit; golf drive; ice hockey slap shot; overhead lacrosse shot and forehand ground stroke in tennis. The swings were considered up to the impact event or ball release, as appropriate.

In order to study the effect of swing weight on swing speed both variables need to be explicitly defined to ensure that all data describes the same property. These definitions are important as they needed to be such that the data provides a fair comparison across all nine sports. The immediate choice of parameter for swing weight was the second moment (m_2), or moment of inertia (I) to describe the implement's rotational resistance, as defined by Brody [9]. There were however, four possible parallel axes which the moment of inertia could be defined about, which were all considered. The axes were all perpendicular to the handle and in plane with the implement's face. The locations were: the centre of mass; the end of the handle; the location of the distal hand; an assumed centre of rotation.

A correlation matrix was created using the variables in Table 1 and alternatives, which provided a clear understanding of the most strongly related variables in the data set and informed decisions as to which were the most suitable definitions.

The moment of inertia about the handle end (I_{HE}) was chosen as the most appropriate definition. This was because it is a definite location on every implement which will not change, as the location of the distal hand or the instantaneous centre of rotation could. It was also possible to calculate, using the dimensions of the implements, the moment of inertia about the centre of mass and the parallel axis theorem. The handle end moment of inertia has a relatively significant relationship ($p<0.1$) with the linear velocity at the implement's tip or impact point. The only other definition for I which correlated as strongly was the moment of inertia about the pivot point. However, there was not enough data available to determine a pivot point for every sport, meaning large approximations would have to have been made, making the handle end a more reliable choice.

Similarly, for the swing speed, there were four possible definitions for the velocity which could be used in analysis: three linear and one rotational. These options were: velocity at centre of mass; velocity at the impact point; velocity at the implement tip; angular velocity. The linear velocities were specified as vectors normal to the implement face and all four definitions were at the time of impact.

After consideration it was decided that the most suitable velocity definition to use would be the linear velocity at the implement tip (V_{TIP}) as it is an unambiguous, unchanging location. The velocity at the impact point would be the most useful velocity to analyse and it does correlate slightly more strongly with I_{HE} that the tip velocity (r^2=-0.60, p=0.086 compared to r^2=-0.59, p=0.095), however the location of the impact point can change between shots and even more so between players, meaning it is difficult to define a constant impact location. This and the fact that the tip velocity has a stronger logarithmic relationship with I_{HE} (r^2=-0.656, p=0.055 compared to r^2-0.621 p=0.074) make V_{TIP} the optimum variable.

3. Results and Discussion

The averaged data values for the most important variables across all nine sports are shown in Table 1, including implement length (l) and mass (M) and the outbound velocity of the impacted object (v_o').

Table 1. Mean data values for all nine sports

Sport	Sources	l (m)	M (kg)	I_{HE} (kgm^{-2})	V_{TIP} (ms^{-1})	t_{swing} (s)	a_{TIP} (ms^{-2})	v_o' (ms^{-1})
Badminton	[10-11]	0.665	0.0897	0.0131	50.36	0.048	1049	57.40
Baseball	[2,4,6,7,12-14]	0.847	0.8468	0.2401	28.14	0.222	127	42.71
Cricket	[15-18]	0.862	1.1271	0.4993	16.52	0.160	46	20.40
Field Hockey	[19-20]	0.928	0.6014	0.2386	26.16	0.170	154	29.82
Golf	[3,21-23]	1.122	0.3160	0.4612	47.38	0.290	163	73.55
Ice Hockey	[24]	1.467	0.5479	0.6008	28.43	0.120	247	22.52
Lacrosse	[25-28]	1.100	0.3700	0.3997	23.68	0.199	123	25.73
Tennis	[29-30]	0.685	0.3418	0.0508	25.85	0.140	185	29.21
Tenpin Bowling	[7, 31-32]	0.714	8.1504	2.1456	9.97	0.600	17	-

The raw data plot of velocity against I_{HE} was not very useful for defining a relationship across the sports because the velocity decreases at an uneven rate with respect to increasing I_{HE}. This effect was normalised by taking the logarithm, to base 10, of the data, producing a log-log plot, as can be seen in Fig. 1. The value for *n* in equation 1, taken from the gradient of the trend line through the data, was found to be 0.22 (r^2=-0.66, p=0.06). This is very comparable with the previous studies of single sports in literature that found n=0.25-0.27 [3-5] and suggests that a global trend might exist across all swinging sports.

There is scatter in the data in Fig. 1, which can be clearly seen and there are several reasons for this. It is partly due to the different way in which the games are played, with each style of action having different characteristics including type of motion and swing time, which can vary by over 0.5s between sports, as can be seen in Table 1.

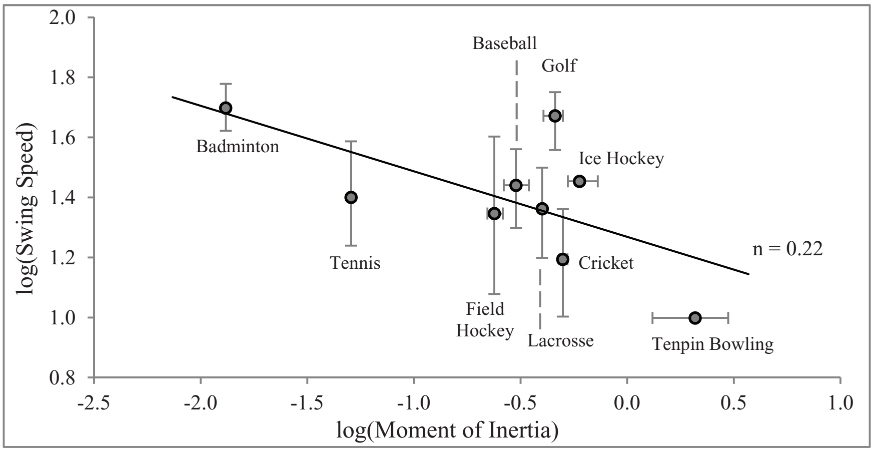

Fig. 1. Log plot of Swing Speed against Moment of Inertia, n=0.22

It is very clear that assuming all of the sports have an equal swing time (t_{swing}) would be inappropriate as, for example, t_{swing} for tenpin bowling is 12.5 times greater than t_{swing} for badminton. The difference in swing time is likely to be partly due to the implement's moment of inertia but it is also partly due to the actual motion, which limits how fast a swing can be. For example a badminton smash, which produces head speed almost entirely from a rotational wrist motion, as found by Kwan et al [8], will allow a quick swing and is a simple motion to analyse. Conversely the forward drive in cricket is a much more complex movement involving the rotation of both arms and a large amount of translation with the step forwards, which is naturally a much slower movement and a more difficult motion to simplify for analysis.

Due to the influence of swing time, this was used to normalise the data further. The tip velocity for each sport was divided by the swing time for that activity to produce a new variable to replace the swing speed: the apparent acceleration at the tip of the implement (a_{TIP}) or the swing acceleration.

The swing acceleration is a much more appropriate variable to use in analysis when considering multiple sports because it removes the factor of swing time. Removing the effect of swing time is important because an athlete performing a swing with a longer swing time can apply an accelerating force to the implement for a longer period of time, potentially speeding up the implement more than if they were performing a shorter swing. Taking the acceleration data also draws the data closer together which produces a more solid relationship as can be seen in Fig. 2. This is shown by the fact that the log data for the acceleration is much more closely correlated with the moment of inertia than the velocity data (r^2=-0.82, p=0.006 compared to r^2=-0.66, p=0.06). This new relationship can be defined in a similar manner to the swing speed relationship in past research as shown in equation 2, where C is a player constant and m is the gradient of the log plot.

$$a = \frac{V}{t_{swing}} = \frac{C}{I^m} \qquad (2)$$

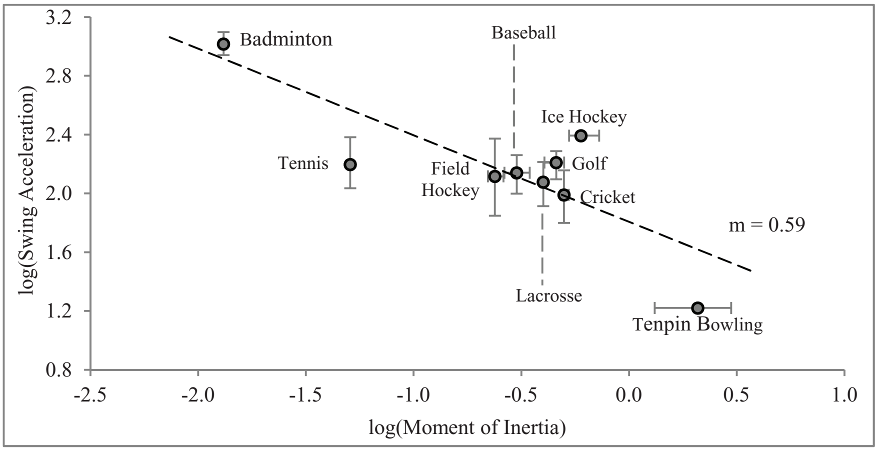

Fig. 2. Log plot of Swing Acceleration against Moment of Inertia, m=0.59

The m value in this case, taken from the acceleration log plot is 0.59. This is quite different to the n value for the swing speed relationship, but the relationship is far more suitable for a multisport analysis.

There is still scatter in the data when using the swing acceleration but the general fit is better than the previous plot. Ice hockey is one of the notable points to sit off the line, which is due to the unusually high acceleration. This could be because in the slap shot in ice hockey, the player has one hand part way down the stick which can apply an extra torque to the stick. Conversely tenpin bowling has a very low acceleration, which could be due to the fact the player has to hold a large mass with just their finger tips and a sudden acceleration could result in dropping the ball.

4. Conclusion

When considering multiple sports it is not appropriate to use the swing speed for analysis, it is the swing acceleration which should be considered. The data suggests that there is a global trend between the swing weight and swing acceleration of implements in different sports. However, more work is required to confirm and validate this relationship and it may be easier to analyse each sport individually then compare the outcomes at a later point.

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