Influences of a rider on the rotation of the horse–rider system during jumping

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Abstract

This study examined the effects of a rider on the angular momentum and angular velocity of the jumping horse, particularly during the flight phase. Sagittal plane video recordings were digitized of eight horses jumping a vertical fence (1 m high) under two conditions: Loose and Ridden. An experienced rider rode the horses during the Ridden condition. Using appropriate segmental inertial data for the horse and rider, angular momentum and angular velocity were calculated for the Loose and Ridden conditions. Estimates of the various rider effects on angular momentum and angular velocity were obtained by comparison of Loose and Ridden conditions and examination of the contributions of the horse and rider segments to the total angular momentum. The results showed that the rider’s effect on angular momentum was significant but that the rider’s segmental contribution to the angular momentum of the horse–rider system was minimal. Repeated-measures ANOVA revealed that the rider had a significant effect on the angular momentum and angular velocity of the horse during the flight phase ($P < 0.01$). However, the rider did not have a significant effect on the transfer of angular momentum during the flight. We concluded that the rider’s instruction has a greater influence on the horse’s motion than the mechanical transfer between rider and horse.

Keywords: horse; jumping; rider effects; angular momentum

Introduction

Jumping horses have been the subject of increasing biomechanical research over the past ten to fifteen years. The majority of these studies have dealt with linear kinematics and kinetics, such as stride characteristics, limb placements, centre of gravity (CG) characteristics at take-off and landing, and ground reaction forces during jumping. Angular considerations, particularly angular momentum, have remained relatively unexplored with few notable exceptions. In human athletes, particularly those involved in jumping or gymnastic events, knowledge of angular momentum control has helped the performers to enhance their techniques, for example the hitch-kick technique in long jumping, or the Fosbury flop in the high jump.

Clayton briefly considered the importance of angular momentum in the jumping horse, however little has been discussed since. Galloux and Barrey conducted an analysis of angular aspects of jumping horses. They also examined the contribution of the principal body segments of the horse and rider to total angular momentum of the system by grouping segments together as follows: the trunk, the head and neck, the forelimbs, the hind limbs and the rider. Inertial parameters for this study were derived from a geometric modelling approach. The riders were included in the analysis, however the rider’s input was not discussed.

Several factors determine jumping success in sport horses, including linear parameters of flight trajectory, and angular motion. Although the horse and rider are separate individuals, for the purposes of this study they are considered as a ‘system’. At take-off the horse–rider system becomes a projectile. The translation of the whole-body CG and rotation of the horse–rider system about the CG are important components of the jump. The flight trajectory of the CG is determined by the horizontal and vertical velocity components at take-off. Angular momentum during the flight phase is generated primarily by eccentric
force at take-off (i.e., a force that does not act through a body's CG). The amount of angular momentum during the flight phase tends to remain constant, although there may be some minor effects caused by variations in air resistance, or forces due to the horse hitting the fence. Controlling rotation during the flight phase of a jump is particularly important in equine jumping. If the horse under-rotates, it is likely to hit the fence with its hind limbs during the flight or landing phases; if the horse over-rotates, there is a possibility that the horse will fall or unseat the rider. Either way, the horse and rider risk poor performance and injury.

It is widely accepted that the rider plays an important role in controlling the horse's motion. Powers and Harrison\textsuperscript{10} have developed a theoretical model that describes the interaction between horse and rider, see Fig. 1. In this model the rider interacts with the horse via several lines of communication. The rider and the horse have separate information processing units, which respond in various ways to stimuli provided by the rider. In practice, small forces applied by the rider via these lines of communication may result in relatively large changes in the movement of the horse–rider system. For example, a small force applied by the rider's legs or hands can result in the horse changing its velocity or direction. These types of effects are achieved by training the horse to respond to the rider's stimuli with appropriately large muscle forces. Powers and Harrison defined this change in the movement of the horse in response to the rider's stimuli as a \textit{behavioural} effect.

The position and motion of the horse–rider system CG can also be affected by changes in the mass distribution of the system. Therefore, the position of the rider's body segments relative to the horse may alter the location of the horse–rider system CG or moment of inertia, and this may result in changes in the angular velocity of the horse–rider system during periods of flight. Powers and Harrison defined changes in the motion of the horse arising from alterations in the rider's mass distribution as an \textit{inertial} effect.

In theory, the \textit{total} effect of the rider on the horse's locomotion is the summation of the \textit{behavioural} and \textit{inertial} effects. These effects on the linear motion of jumping horses have been described previously\textsuperscript{11}, however the extent to which the rider affects the rotation of the horse–rider system during jumping is relatively unknown. Understanding the nature of the rider's effect on the angular motion of the horse may help improve methods of training and coaching during jumping.

There are, however, various problems involved when analysing the rotational motion of the horse–rider system. Difficulties have existed in equine angular momentum calculations because of the lack of accurate data on the inertial parameters of the horse. In studies on humans, probably one of the main sources of error in biomechanics research comes from the use of inappropriate estimates of segmental inertial data\textsuperscript{12}. There is little reason to believe that the same conclusions could not be drawn for equine subjects. Recent work by Buchner \textit{et al.}\textsuperscript{13} has provided accurate body segment parameters from Dutch Warm-blood horse cadavers including segmental moments of inertia.

The overall aim of this study was to obtain an understanding of the role of the rider in controlling the angular motion of the horse–rider system:

- The first objective was to measure the total effect of the rider on angular momentum and angular velocity of the horse–rider system by comparing Loose and Ridden horses.
- The second objective was to determine if the rider had a significant effect on the mean angular momentum and angular velocity of the horse.
- The third objective was to measure the contributions of the rider and the principal segments of the horse to the total angular momentum and make comparisons with the work of Galloux and Barrey\textsuperscript{9}.

\textbf{Methods}

\textbf{Subjects}

Eight young horses were chosen for the investigation (age range: 3–5 years). The horses were Irish Sport Horses, and their masses ranged from 520 kg to 620 kg (mean = 570 ± 4 kg). The horses had been in

\textbf{Fig. 1} Stimuli affecting the horse during jumping. Adapted from Powers and Harrison\textsuperscript{10}.
training for about 6 months. An experienced rider (70 kg) was chosen to ride all the horses. In accordance with national guidelines, informed consent was obtained from all horse owners before participating in this experiment.

A 21-segment anthropometrical model derived from the data of Buchner et al.\(^{13}\) was used for the horse. As the fence was only 1 m high and the rider was experienced, the rider’s motion was considered symmetrical. Since only one side of the rider was visible to the camera, it was assumed that a six-segment model was an appropriate representation of the rider’s motion. A six-segment model was selected for the rider\(^{14}\). Retro-reflective markers were glued to the left side of the horse and rider at the appropriate anatomical landmarks for the selected anthropometrical data.

**Video capture**

Video recordings took place in a well-lit indoor arena. A single Panasonic AG450 camcorder and tripod were set up along one side of the arena, perpendicular to and 20 m from a vertical fence measuring 1 m high. The camera was at a height of 1.30 m, and was horizontally levelled using a spirit level. The shutter duration was set at 0.002 s. The field of view measured approximately 1 m wide, and encompassed approximately one and a half approach strides, the take-off, the flight, the landing, and part of the departure phase.

Horses were given a short warm up before each session (trotting and cantering), and were allowed a few practice jumps (0.7 m to 0.9 m high) before video recording. SVHS video recordings (50 Hz) were obtained of the subjects jumping the fence under two conditions: Loose (without a rider and tack) and Ridden. All horses were required to jump the fence at a canter. Recordings were randomized between Ridden and Loose trials. Trials took place over two consecutive days with horses attempting between two and four jumps on each day. Fatigue and learning effects were deemed negligible.

**Digitizing**

Two successful jumping attempts for each horse under each condition were selected for analysis. Trials were excluded if horses broke into a trot before the fence, or jumped the fence in an abnormal way. For calibration purposes, reference markers placed 4 m apart on either side of the fence were digitized in the plane of the horse’s jump prior to filming. The precision of the digitizing process was calculated as 0.05% of the diagonal field of view in accordance with the method outlined by Pedotti and Ferrigno\(^{15}\). This precision score is generally typical of video-based digitizing systems.

The video sequences were digitized manually using Peak Motus 3.2 (Peak Performance Technologies, Englewood, CO, USA). Although one camera was used, it was possible to digitize all limbs of the horses since both sets of the horses’ limbs were visible apart from three proximal joint centres of the right limb set: these were the femoro-tibial joint, the scapulo-humeral joint and the humero-radial joint. The location of these joint centres could be estimated from knowledge of equine anatomy, and by the orientations of the distal portions of the limbs.

The CG of each of the 21 body segments of the horse was determined from the segmental coordinates using the anthropometrical data of Buchner et al.\(^{13}\). The CGs of each of the six segments of the rider were calculated using the data of Winters\(^ {14}\). Inertial parameters for the horse were taken from the data of Buchner et al.\(^{13}\) who calculated body segment parameters (BSPs) for Dutch Warmblood horses. These horses were similar in body size and mass to the horses used in this study. The actual BSPs used for each horse were obtained by matching the individual horse mass to a horse of similar mass in the Buchner et al.\(^{13}\) database. Segmental moments of inertia values as calculated by Whitsett\(^ {16}\) were used for the rider. During Ridden trials, the mass of the saddle (9 kg) was added to the horse’s trunk segment.

**Data analysis**

Raw coordinate data were smoothed in Peak Motus with a Butterworth filter using the Jackson knee optimization method\(^ {17}\). Cut-off frequencies ranged from 2 to 4 Hz for x coordinates and 3 to 6 Hz for y coordinates. Filtered coordinate data from Peak Motus were exported to Microsoft Excel. The coordinates of the total body CG were determined from the segmental coordinate and inertial data using the sum of moments method\(^ {18}\). Visual basic macros were used to calculate angular momentum and angular velocity for the horse and rider. For direct comparison, angular momentum and angular velocity were calculated around the horse’s CG for each condition. For a horse–rider system with 27 segments, angular momentum was calculated using the following generalized equation (for the Loose condition, there were 21 segments):

\[
\mathbf{H}_{\text{TOTAL}} = \sum_{x=1}^{27} (I_x \omega_x + m_x d^2 \omega_x)
\]

where \(\mathbf{H}_{\text{TOTAL}}\) is the total angular momentum of the multi-segment system, 27 is the number of segments of the horse and rider model, \(I_x\) is the segment’s moment of inertia with respect to a transverse axis through the segment’s own CG, \(\omega_x\) is the segment’s angular velocity with respect to a transverse axis
through the segment’s own CG, \( m_s \) is the mass of the segment, \( d \) is the distance between the segment’s CG and the horse’s CG, and \( \omega_k \) is the angular velocity of the segmental CG about the principal transverse axis (i.e. horse’s CG).

The axes conventions and an example of the variables involved in calculating angular momentum are illustrated in Fig. 2.

Total moment of inertia (\( I_{\text{TOTAL}} \)) was calculated using the following equation:

\[
I_{\text{TOTAL}} = \sum_{s=1}^{s=27} (I_s + m_s d^2)
\]

Total angular velocity (\( \omega_{\text{TOTAL}} \)) was calculated using the following equation:

\[
\omega_{\text{TOTAL}} = \frac{H_{\text{TOTAL}}}{I_{\text{TOTAL}}}
\]

To compare the different jumping attempts for each horse in the same relative time scale, the angular momentum and angular velocity time-histories were re-sampled and normalized using a cubic spline re-interpolation in Matlab (The MathWorks, Inc., MA, USA). This involved identifying four distinct phases of the jump in accordance with Clayton19. These phases are defined in Table 1, and illustrated in the form of a typical angular momentum curve in Fig. 3. Each phase was normalised to a standard percentage of the overall jump period. The phase percentages were calculated from the average of the times spent by each horse for each jump phase for all trials and conditions. The phase percentages were: Approach 35%, Take-Off 19%, Flight 25% and Landing 21%. This method is similar to that reported previously9.

For comparison and replication of the Galloux and Barrey9 study, the relative contributions of the principal body segments of the horse and rider to the angular momentum were calculated for the Ridden condition. Angular momentum of the five principal body segments was defined as follows:

- **Trunk:** the horse’s trunk segment
- **Head & neck:** summation of the horse’s head and neck segment
- **Rider:** summation of all the rider’s segments
- **Forelimbs:** summation of the horse’s scapula, humerus, radius, metacarpus and forelimb digit of both limbs
- **Hind limbs:** summation of the horse’s femur, tibia, metatarsus and hind limb digit of both limbs

The relative variability of angular momentum during flight was obtained using the coefficient of variation (COV), and comparisons of the COV were made between this study and Galloux and Barrey9. The COV was calculated using the formula:

\[
\text{COV} = \frac{\text{SD}}{\text{Mean}} \times 100
\]

Mean values for angular momentum and angular velocity were calculated for each jumping condition and comparisons were made among the resulting graphs by qualitative inspection.

**Table 1** Definition of the jump phases analysed in the study

<table>
<thead>
<tr>
<th>Phase</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approach</td>
<td>This is the last complete stride before take-off, and represents the period</td>
</tr>
<tr>
<td>Stride 1</td>
<td>from impact of the TrH until the impact of the TrH at take-off</td>
</tr>
<tr>
<td>Take-off</td>
<td>This represents the period from impact of the TrH until lift-off of the</td>
</tr>
<tr>
<td></td>
<td>LdH in the jump stride</td>
</tr>
<tr>
<td>Jump flight</td>
<td>This is the period from lift-off of the LdH at take-off until impact of the</td>
</tr>
<tr>
<td></td>
<td>TrF at landing</td>
</tr>
<tr>
<td>Landing</td>
<td>This represents the period from impact of the TrF after the jump flight</td>
</tr>
<tr>
<td></td>
<td>until the succeeding impact of the TrH</td>
</tr>
</tbody>
</table>

TrH: trailing hind limb; LdH: leading hind limb; TrF: trailing forelimb.
A repeated-measure ANOVA was used in SPSS 11.0 (SPSS Inc., Chicago, IL, USA) to test for significant differences in the mean angular momentum and angular velocity during the flight phase of the jump between Loose and Ridden conditions.

Results

Horses made contact with the fence on 10 occasions during the Loose condition and four occasions during the Ridden condition. In all cases, the fence remained upright without the pole being dislodged.

Due to the combined effects of the trial averaging, filter distortion and the sampling frequency, it is not possible to identify the event of landing on the graphs as an instantaneous event. The event of landing is therefore represented on the graphs as a brief time band rather than a precise event line. It is also important to note that the point marks on the graphs do not represent sample data points; they serve only to identify each of the graph lines.

The mean total angular momentum was found to be almost constant during the flight phase of the jump for Loose and Ridden conditions, and this is illustrated in Fig. 4. A general reduction in the absolute magnitude of angular momentum throughout the jumping sequence was evident in the Loose condition when compared with the Ridden condition.

The relative contributions of the rider and the principal body segments of the horse on the total angular momentum of the horse–rider system are shown in Fig. 5. The trunk segment generated a smaller contribution to total angular momentum than the head and neck, forelimb or hind limb segments. The rider provided only a small contribution to angular momentum during the jumping sequence, and this was minimal during mid-flight. There is some evidence of transfer of angular momentum among the segments during the flight phase. The most obvious indication of this is an increase in the angular momentum of the forelimbs, which is reciprocated by a decrease in angular momentum of the head and neck segment.

Figure 6 shows the mean angular momentum of the horse–rider system compared with the mean angular momentum of the horse alone (i.e. the summation of the angular momenta of all the horse segments of the ridden horse). It can be seen that these lines are very similar throughout the jumping sequence, indicating that the rider’s contribution to the total angular momentum of the horse–rider system is minimal.

The angular velocity for Loose and Ridden conditions is shown in Fig. 7. During the flight phase, the mean total angular velocity was also found to be almost constant. It is evident throughout the jumping sequence that the Loose condition did not achieve as
high a level of angular velocity as did the Ridden condition.

Table 2 presents the results of the ANOVA comparing angular momentum and angular velocity in Loose and Ridden conditions during the flight phase. These data show that during flight, the mean angular momentum and angular velocity of the horses were significantly higher in the Ridden condition compared with the Loose condition.

Discussion

Uniquely, this study has used segmental data taken from equine cadavers to calculate the angular momentum and angular velocity for the jumping horse. The results indicate that the rider significantly increased the angular momentum of the system during flight (see Fig. 4 and Table 2). The mean difference between the Ridden and Loose conditions during flight was 91 kg m$^2$ s$^{-2}$ (i.e. approximately 22%). While this demonstrates that the effect of the rider on the system was substantial, these data alone do not provide a very useful insight into the role of the rider since it is plausible that the higher angular momentum of the Ridden condition could be entirely explained by the greater mass of the horse–rider system.

It has been proposed that the rider’s effect may be partitioned into behavioural and inertial components$^{10}$. Figure 5 shows that the contribution of the rider’s segments to the overall angular momentum of the system was very small throughout the flight period. This suggests that the inertial effect of the rider in controlling angular momentum during flight was minimal. Since the total effect of the rider on the angular momentum of the system was significant and the inertial effect appeared to be minimal, it is therefore likely that the major effect of the rider on the angular momentum of the system was a behavioural effect. Figure 5 also shows that the angular momentum of the rider remained relatively constant throughout the flight period and this suggests there was very little transfer of angular momentum between the horse and rider segments during the flight period. Inspection of Fig. 7 confirms this, since the angular velocity of the horse–rider system also remains constant throughout flight. This suggests that during the flight phase the rider’s movements had very little influence on the rotational motion of the horse–rider system.

Figure 6 provides a comparison of the segmental contribution of the horse angular momentum with the angular momentum of the horse–rider system. These data show that the segmental contribution of the horse segments accounts for virtually all of the angular momentum of the horse–rider system throughout all phases of the jump. While the rider’s mass represented approximately 11% of the horse–rider system mass, the mean contribution of the rider’s segments to the total angular momentum during the flight phase was much lower at 1.7%. This is probably due to the fact that the rider sits with his/her legs relatively fixed around the horse’s trunk close to the horse’s CG. The only body segments available to substantially influence the angular momentum of the horse–rider system are the upper portion of the rider’s trunk (i.e. above the waist) and the head/neck and arm segments, which represent much less than the rider’s total mass. Therefore, the rider’s potential to influence the angular momentum of the system is reduced. This suggests that the instruction and control of the horse had a greater influence on angular momentum than the mechanical transfer between the horse and rider especially during the flight and landing phases.

The angular momentum and angular velocity results in this study were quite different from those of Galloux and Barrey$^9$. During the flight phase for the Ridden horse, Galloux and Barrey$^9$ calculated an angular momentum value of $722 \pm 125$ kg m$^2$ s$^{-2}$, whereas in this study the value for the Ridden horse was $409 \pm 61$ kg m$^2$ s$^{-2}$. The relative contributions of the segments to the total angular momentum were also quite different from those found by Galloux and Barrey$^9$. Angular velocity results from Galloux and Barrey$^9$ were also larger at $2.09 \pm 0.09$ rad s$^{-1}$.

Table 2 Mean angular momentum and angular velocity during the flight phase for Loose and Ridden conditions

<table>
<thead>
<tr>
<th>Variable</th>
<th>Loose</th>
<th>Ridden</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular momentum (kg m$^2$ s$^{-1}$)</td>
<td>318 ± 62</td>
<td>409 ± 61</td>
<td>0.002</td>
</tr>
<tr>
<td>Angular velocity (rad s$^{-1}$)</td>
<td>1.42 ± 0.19</td>
<td>1.61 ± 0.13</td>
<td>0.017</td>
</tr>
</tbody>
</table>
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compared with $1.61 \pm 0.13 \text{rad s}^{-1}$ in this study. These contrasts were probably the result of three methodical differences between the studies:

1. Galloux and Barrey\textsuperscript{9} used a higher fence, and the mean mass of the horses was slightly greater; this probably accounts for the higher overall angular momentum values.

2. Galloux and Barrey\textsuperscript{9} used segmental mass proportion and CG loci data from Kubo et al.\textsuperscript{20} where the proximal limb segments are incorporated into the trunk segment. They also used inertial data derived from geometrical modelling. Previous research has indicated the weakness of geometrical models in calculating accurate segment moments of inertia, some of which can result in large errors\textsuperscript{21}. The use of BSP data from these two sources could further compound the inaccuracies of the angular momentum calculations.

3. Galloux and Barrey\textsuperscript{9} digitized only one side of the horse and rider and it was assumed that the visible side represented the contralateral limb pair. This may be a reasonable assumption for the rider (and for the horse during mid-flight); however this is not the case for the horse during the approach, the take-off or the landing phases.

Despite some methodological shortcomings, the Galloux and Barrey\textsuperscript{9} study represented an important initial step in describing the segmental components of angular momentum in the jumping horse. It is evident from the results in the present study that use of cadaver-based inertial values for the body segments for the horse has enhanced the angular momentum results. This is apparent from the almost constant angular momentum during the flight phase (see Fig. 4), and the lower coefficient of variation (4.7% versus 17.3%) in the angular momentum result during the flight phase in the Galloux and Barrey\textsuperscript{9} study. This shows that the Galloux and Barrey\textsuperscript{9} results are relatively more variable than those in this study.

The factors that influence the \textit{behavioural} effect of the rider on the horse are as yet unclear and merit further investigation. For example, instrumenta-
tion of the saddle, the bit and the rider’s legs may be used to investigate forces and impulses via the lines of communication between horse and rider\textsuperscript{10}. The present study examined horses in the sagittal plane only, as this is the most important plane in horse jumping. Lateral movement of the horse’s body segments during jumping is usually minimal; however the rider’s lateral movement may be more substantial, and this may have important effects on the three-dimensional characteristics of the horse during jumping.

Conclusions

This study concludes that the main effect of the rider in controlling rotation of the horse during jumping is likely to be determined before the point of take-off. The practical implications of this study indicate that the actual mass and mass distribution of the rider (i.e. \textit{inertial} effect) had a minimal influence on the rotation of the horse, and that the main effects of the rider came from the rider’s instruction and communication with the horse (i.e. \textit{behavioural} effect). During training, many horse-riding coaches spend much of their teaching time on the body position of the rider during jumping, which, based on the results of this study, may not be as important as previously thought. There are, however, many further aspects that require investigation, for example the effects of riders of different body size and mass and ability, and the effects of larger fence heights on the rotational characteristics of jumping horses.

References


12. Hinrichs RN (1985). Regression equations to predict segmental moments of inertia from anthropometrical


