Maximum Velocities in Flexion and Extension Actions for Sport

by
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Speed of movement is fundamental to the outcome of many human actions. A variety of techniques can be implemented in order to maximise movement speed depending on the goal of the movement, constraints, and the time available. Knowing maximum movement velocities is therefore useful for developing movement strategies but also as input into muscle models. The aim of this study was to determine maximum flexion and extension velocities about the major joints in upper and lower limbs. Seven university to international level male competitors performed flexion/extension at each of the major joints in the upper and lower limbs under three conditions: isolated; isolated with a countermovement; involvement of proximal segments. 500 Hz planar high speed video was used to calculate velocities. The highest angular velocities in the upper and lower limb were 50.0 rad·s-1 and 28.4 rad·s-1, at the wrist and knee, respectively. As was true for most joints, these were achieved with the involvement of proximal segments, however, ANOVA analysis showed few significant differences ($p<0.05$) between conditions. Different segment masses, structures and locations produced differing results, in the upper and lower limbs, highlighting the requirement of segment specific strategies for maximal movements.

Key words: maximal; angular; velocity; movement pattern.

Introduction

Speed of movement is fundamental to the outcome of many human actions. Protective motions, trip and fall recovery (van den Bogert et al., 2002) as well as sporting actions may all be more successful if the performer is able to move at greater speed with minimal loss of movement accuracy. In sport, athletes who are able to move faster than their opponents may complete a given task more quickly, or use this advantage to reduce the opponent's time to react and respond.

It is within the sporting arena that most effort has been focused on how to move limbs with maximum velocity (Escamilla, 1998 in baseball pitching; Fortier et al., 2005 in sprinting and Glazier et al., 2000 in cricket bowling to name but a few). A variety of strategies can be implemented in order to maximise movement speed depending on the goal of the movement,

constraints on the movement range, and the time available to perform the movement. With this in mind, most research has focused on task specific movements or, as outlined below, the absolute maximum velocity some end point or object can be endowed with.

The use of a countermovement to produce a stretch shorten cycle is a basic movement pattern that previous studies have shown increases the velocity of the resulting movement (Bobbert et al., 1986; Bartlett, 2000; Takarada et al., 1997). Along with the countermovement a fundamental strategy for maximising velocity is completing movements over a large range to increase the time in which an athlete can accelerate a limb. This can be seen in throwing events in track and field athletics, bowling in cricket, pitching in baseball, and place kicking in

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rugby and soccer, where there are few constraints on time and technique. This tends to utilise a proximal to distal sequence, where segments at the proximal end of the chain reach their peak velocity and then slow by transferring momentum to distal segments. This sequencing has been identified in a number of sporting actions, including baseball pitching (Stodden et al., 2001; Wang et al., 1995), American football passing (Fleisig et al., 1996) and javelin throwing (Alexander, 1991). Such movement patterns are often considered to be whip like. LeBlanc and Dapena (2002) considered that a greater delay in the sequencing of muscle activation in the kinematic chain allowed more energy to be transferred along it whereas others (Alexander, 1992) suggested that this may be an oversimplification. Differences of opinion in this area are thought to be due to the differences and interactions between segment orientation, angles, masses and loads involved in different actions as well as throwing style and a skill level (Neal and Snyder, 1991; Putnam, 1993). In the lower limb it is often considered that it is active acceleration of distal segments that decelerates proximal ones such as seen in Sørensen et al.'s (1996) examination of the martial arts high front kick. Here the deceleration of the thigh was caused by an increase in velocity of the shank giving rise to a flail like rather than whip like motion.

In contrast to the abundance of data on sport specific maximal velocities, it seems that, in all but a few cases (Bobber et al., 1987; Pertuzon and Bouisset, 1971), single isolated joint velocity data are restricted to activities performed on iso-velocity dynamometers. These dynamometers are normally restricted to angular velocities well below 500 ·s-1 (8.73 rad·s-1). Studies which state they are performing slow and fast trials have tended to use 240 to 300 ·s-1 (4.19 – 5.24 rad·s-1) for the fast trials (Aagaard and Andersen, 1998; Brown and Whitehurst, 2003; Coyle et al., 1981). Data gained using such methods are commonly used to determine joint torque-angle-angular velocity relationships for use in computer simulation models. However, it is likely that such an approach will underestimate joint torque at higher concentric velocities (Forrester et al., 2011).

Maximal isolated joint angular velocities do not seem to have been well reported in the literature. For many activities countermovements

are the natural movement mode and the inclusion of proximal segments would normally be considered to give the highest movement velocities. Currently there are no data on how movement velocity changes with systematic modifications of movement conditions; isolated to a single direction about a joint, with a countermovement and with proximal segments involved. These systematic changes may be different in the upper and lower limbs. Knowledge of such movement strategies is useful in combat sports where athletes must perform movements in restricted time frames, without providing visual cues or noticeable repetition of movement patterns. Examining maximum isolated joint angular velocities would also be useful for further work in conjunction with muscle modelling. Thus, the aims of this study were as follows: to discover maximum isolated joint angular velocity values for flexion-extension actions; examine the effects of a countermovement on isolated joint angular velocity; and examine the effect of 'same movement plane' proximal joint movements on joint angular velocity. The results provide a useful database of values to supplement data obtained from compound movements and dynamometer studies for sports analysis and muscle modelling.

Material and Methods

Participants

Seven university level to international level male athletes, who were involved in sports that required fast movements of the upper and lower limbs (kayaking, taekwondo and karate) took part in the study (age 22 ± 2.2 yrs, body height 1.74 ± 0.05 m and mass 71.9 ± 11.3 kg). It was considered that using skilled, athletic subjects would reduce subject injury risk due to familiarity with the types of action being performed and that it would give a better representation of maximal velocities. Informed consent was gained from all subjects and the study was conducted in accordance with approval given by the Loughborough University ethical advisory committee.

Procedures

Filming was conducted using one Phantom V 4.1 high speed digital video camera, mounted on a Manfrotto rigid tripod, with a sample rate of 500 Hz and a shutter speed of

1100μs. In plane linear calibration in both the horizontal and vertical directions was performed with one metre calibration rods prior to each subject testing. Joint centres were manually digitised using Phantom digitising software with a resolution of 4 mm in a 2 m by 1.5 m calibrated area. A 2-D manual digitising method was preferred over electro-goniometers, magnetic tracking or marker tracking methods that involve the attachment of equipment to the subject's body in order to prevent restriction of movement. Measurements by such equipment during very dynamic actions are also affected by skin and other soft tissue movements. Even using lightweight retroreflective markers can cause errors in predicted joint centre location of more than 20 mm for the upper limb during dynamic actions (Roosen et al., 2009).

Subjects were allowed time to perform a warm up of their choice and practice each task. Trials were recorded when subjects had become accustomed to the actions and were able to voluntarily isolate each movement without further additional restraint either by themselves or by a researcher. Subjects then performed separate flexion and extension trials at the shoulder, elbow, wrist, hip, knee, and ankle on their dominant side under the following conditions: all movement isolated to the joint being analysed in a single direction at a time (ISO), all movement isolated to the joint being analysed and using a countermovement (CM), using a countermovement and the involvement of proximal segments (unrestricted, UR).

For flexion trials, the flexion movement was called the positive movement. For extension trials the extension movement was called the positive movement. Subjects were asked to perform each action so that during the positive movement they reached the maximal angular velocity that they could safely obtain. Further attempts were permitted until it was felt by the subject and by a researcher that the action was performed in accordance with the performance criteria of using only the required joints and maximising velocity. Multiple trials per condition were recorded and only those that fulfilled the performance criteria when examined in slow motion were retained for further analysis.

For the UR trials all movement of proximal segments was kept in the same movement plane, but otherwise the subject was allowed to move freely. However, this planar restriction did eliminate almost all torso movement. Subjects were free to position their limbs and move in a range along the movement plane they found comfortable. For leg movements subjects were not permitted to aid the movement by pushing off from the floor with the moving limb. Pictures 1 and 2 show how subjects typically positioned themselves for ISO conditions at each joint.

Statistical analysis

Data were scaled, filtered (Butterworth 2nd order, low pass digital filter, zero phase lag) and numerically differentiated using MatLab version 7.9. Cut off frequencies were determined by visually inspecting the resulting acceleration curves from each trial so that reversals in acceleration did not occur quicker than possible for controlled human movement. Using the information gained from filtering each joint of each subject a single value for filtering at each joint was calculated. The raw data were then filtered using the mean average integer value of all the trials of all subjects at a single joint. This was to allow comparison between subjects for each movement at a given joint, possible differences or similarities could otherwise be artefacts due to different filtering levels. The level of filtering was allowed to vary between joints due to the differing angle ranges, velocities and accelerations that were achieved at each joint.

Segment angles to the horizontal were calculated using the digitised joint centres and joint angles were calculated based on the difference between the angles of the segments in each frame. Angular velocity was obtained by numerically differentiating the joint angle data. For each subject, peak angular velocities were identified for each joint and condition and mean values were taken across subjects. A Lilliefors test ($p < 0.05$) was used to check for normality and with normality indicated, a one way ANOVA with Tukey-Kramer post hoc tests were used to assess differences between conditions ($p < 0.05$). All statistical tests were performed using Matlab version 7.9.

Results

The largest angular velocities per joint were under UR conditions whereas the lowest angular

velocities were split between ISO and CM conditions, although few results were significantly different between conditions.

For flexion movements, angular velocities increased distally along the upper limb for each condition (Table 2). In extension this was only true for the UR condition where the highest angular velocity of any movement was seen at the wrist (mean = 50.0 ± 13.4 rad·s⁻¹). Only UR flexion and UR extension velocities at the wrist were significantly higher across conditions and this held true compared to both the ISO and CM conditions.

For the lower limb it can be seen that knee angular velocities were higher than the hip and ankle velocities under all conditions (Table 3). UR knee extension gave the highest lower limb angular velocity (28.4 ± 3.6 rad·s⁻¹) and was shown to be significantly greater than in the ISO condition. However, no other results within the same joint were shown to give significant differences.

In some cases the magnitude of the standard deviation seems large. Indeed individual results reflected the activities for which the athletes were most highly trained. For example, at the knee martial artists appeared to achieve the highest velocities under ISO conditions (maximum 26 rad·s⁻¹ and range = 14 rad·s⁻¹), however, they performed proportionately less well for UR trials compared to sprinters.
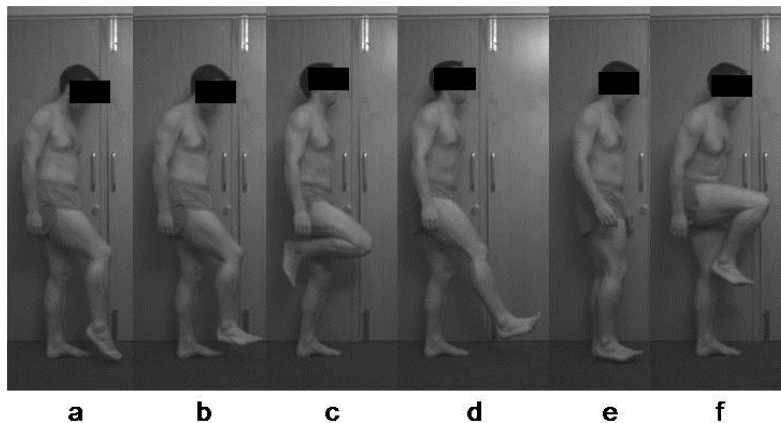
Picture 1

Start positions for lower limb movements.
a = dorsiflexion, b = plantar flexion, c = knee extension,
d = knee flexion, e = hip flexion, f = hip extension.

Picture 2

Start positions for upper limb movements.
a = wrist flexion, b = wrist extension, c = elbow flexion,
d = elbow extension, e = shoulder flexion, f = shoulder extension.

Table 1

Level of filtering used at each joint.

Joint	Level of filtering (Hz)
Wrist	18
Elbow	16
Shoulder	12
Ankle	12
Knee	14
Hip	10

Table 2

Upper limb average maximum angular velocities

Joint	Angular Velocity (rad·s⁻¹)					
	Flexion			Extension		
	ISO	CM	UR	ISO	CM	UR
Shoulder	15.0 ± 2.9	16.6 ± 2.9	17.6 ± 2.5	18.6 ± 3.6	16.1 ± 2.0	18.7 ± 2.8
Elbow	18.6 ± 3.0	17.4 ± 3.6	19.9 ± 1.5	25.6 ± 5.8	25.1 ± 5.7	27.9 ± 3.7
Wrist	23.3 ± 4.9	25.0 ± 5.9	44.4 ± 8.3*	21.3 ± 4.5	23.1 ± 7.7	50.0 ± 13.4*

* Result significantly different to the ISO and CM condition

Table 3

Lower limb average maximum angular velocities

Joint	Angular Velocity (rad·s⁻¹)					
	Flexion			Extension		
	ISO	CM	UR	ISO	CM	UR
Hip	12.0 ± 1.2	11.6 ± 1.3	12.0 ± 1.6	12.4 ± 2.8	13.3 ± 1.4	14.1 ± 2.6
Knee	16.6 ± 5.2	18.1 ± 2.5	18.6 ± 3.5	22.4 ± 3.6	24.3 ± 3.4	28.4 ± 3.6+
Ankle	8.0 ± 3.2	7.9 ± 3.8	12.7 ± 4.5	10.7 ± 3.3	9.1 ± 2.5	12.6 ± 5.1

+Result significantly different to the ISO condition

Discussion

The aim of the study was to establish maximum angular velocities for flexion-extension movements under isolated, countermovement and unrestricted conditions. Results for maximum angular velocity of the upper limb were lower than those found in unconstrained sporting actions. Elbow extension reached 27.9 rad·s-1 under the ISO condition. In baseball pitching this may reach 80.3 rad·s-1 in top pitchers (Fleisig et al., 1996a). Wrist flexion was also found to be higher for baseball pitching, 58.6 rad·s-1 (Vaughn, 1985, cited in Fleisig et al., 1996b) compared to 44.4 rad·s-1 achieved in this study, even though

the hand holds a baseball with a mass of 0.145 kg. Shoulder extension was 18.7 rad·s-1, less than half the shoulder extension velocities we measured from top cricketers during fast bowling, 48.9 rad·s-1.

Maximal angular velocities for the lower limb were closer to those seen in the literature during unrestricted movements. Hip flexion and knee extension values of 12.0 rad·s-1 and 28.4 rad·s-1, both achieved in the UR condition, are comparable to soccer kicking, 14.0   1.0 rad·s-1 and 30.5   4.9 rad·s-1 (Levanon and Dapena, 1998) and slightly higher than knee extension in a martial art high front kick, 26.0 rad·s-1 (Sørensen et al., 1996).

The upper limb appeared to be more affected with the changes in conditions from ISO or CM to UR. This is perhaps expected as the distal segments have a greater number of segments preceding them from the ground in the kinematic chain, and have lower moments of inertia compared to the lower limbs and the torso. Therefore, the upper limbs can obtain the greatest benefit from proximal to distal sequencing and passive transfer of momentum and energy across a joint with regard to maximising angular velocity. It is worth noting here that few significant differences were observed between conditions. Those that were seen were at the wrist where the effects of proximal to distal sequencing are greatest, but not at the ankle. It would seem that the differences between the upper and lower limbs observed in the present study would support the claims that it is not as simple as introducing longer delays between segments in all cases and upper and lower limb strategies for maximising velocity can be different.

CM shoulder extension, elbow flexion and extension, hip flexion and ankle flexion and extension were lower than for the ISO condition. With regard to the martial arts subjects, they would be more practiced at performing the ISO than CM actions, however, it is more likely mechanically disadvantageous positioning that produced these results. For example, in knee flexion the shank was pulled upwards with the hips slightly flexed. In activities such as sprinting, knee flexion would pull the shank with the hips extended, putting the hamstrings muscle under a greater stretch and working through a greater range of motion. However, this requires dynamic

motion to get to this position, and transfer of momentum, so it is no longer isolated. These results indicate that a number of leg techniques in combat sports, which involve similar motions to those studied here, would not benefit from countermovements in terms of angular velocity, and that the countermovements could be detrimental to the overall performance due to increased movement time and an additional cue for the opponent.

The comparisons with results from other studies need to be interpreted whilst keeping in mind that in most cases the literature values are from unconstrained movements where the rotation of the pelvis and trunk is common e.g. cricket, baseball, and kicking for distance. In all these activities large ground reaction forces are produced, predominately on one foot, followed by torso rotations, which aid in the development of velocity in the contra-lateral limb. Use of equipment in some sports may also aid the velocity of the final motion by optimising the forces generated during the countermovement and maximising the positive work done during the positive movement. The differences between unconstrained values and the values measured in this study give an indication of the increase in velocities derived from utilising actions that produce high ground reaction forces and torso rotation. Where the values in this study are comparable to unconstrained literature values, it would indicate that the unconstrained movement is not needed to maximise velocity, however, it may be needed for other reasons such as positioning and coordination.

With limitations, the isolated movement data determined in this study can also be used when determining the torque-velocity relationships required for muscle modelling (Yeadon et al., 2006). Some of these limitations are: that the joint will always be under some load so it will never be the true maximal shortening velocity, and as such will always be a lower limit; two joint muscle actions cannot be accounted for and will be affected by other joint angles, however, these are often not accounted for in torque modelling; the range of motion is limited to that physically possible, which may not be within the range that allows a theoretical maximum to be achieved due to reflexes and joint protection. These limitations tend to

underestimate the maximal velocity of shortening so at least a lower bound can be determined.

The results of the study demonstrate the maximum angular velocities expected at each joint for males during flexion and extension under specified conditions. These results provide: values for fast and slow angular velocities for isolated movements, insight into what velocity regimes these restricted movements could be utilised effectively in combat sports, and provide a lower bound for maximal velocity of shortening values for torque muscle modelling. In sports where total movement time and maximal velocity often need to be traded off, such as combat sports or throwing/kicking against a reacting opponent, these results indicate that for the more proximal joints increasing the isolated motion velocity would be of great advantage. For motions that have little torso axial rotation the athlete would still have near maximal joint velocity but without a cue from a countermovement or other body motions giving time for the defender to respond. For actions dependent on the most distal joint the transfer of power through the system by proximal to distal sequencing is essential for maximal angular velocity and so coordination is more important to develop. With this in mind athletes and coaches need to clearly distinguish between which joints are key for their sport before looking to improve isolated joint velocity or joint velocity from proximal to distal sequencing.

Acknowledgements

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