APPLICATIONS TO THROWING OF RECENT RESEARCH ON PROXIMAL-TO-DISTAL SEQUENCING

R.N. Marshall
The University of Auckland, Auckland, New Zealand

Most assessments of segmental sequencing in throwing, striking or kicking have indicated a proximal-to-distal sequence; until recently, the role of long-axis rotations had not been adequately quantified. Data showing the timing and importance of upper arm internal-external rotation and pronation-supination in throwing and striking have been considered from conventional concepts of proximal-to-distal sequencing. In general, long-axis rotations reached their peak angular speeds late in the skills, although variations are seen as a result of ball size or mass, the magnitude of external forces and use of a racquet. This analysis indicates it is essential to consider longitudinal axis rotations in explaining the mechanics of throwing and striking movements as well as in developing coaching emphases, strength training schedules, and injury prevention programmes.

KEY WORDS: proximal-to-distal sequencing, kinematics, throwing, racquet sports

INTRODUCTION: Many sports demand that maximum speed be produced at the end of the distal segment in a kinematic chain. In throwing activities, for example, athletes try to generate a large hand velocity in a particular direction. Sports that use an implement to increase end point speed, such as tennis or squash, require that the racquet head develops maximum speed.

The idea that there is a ‘grand plan’ that would explain the multitude of different, yet similar, throwing or striking movements is appealing. Indeed, research has suggested that throwing, striking and kicking skills all exhibit aspects of proximal-to-distal sequencing. The concept upon which most others appear to have been developed is the ‘summation of speed principle’ (Bunn, 1972). The ‘kinetic link principle’ (Kreighbaum and Barthels, 1985) and Plagenhoef’s (1971) ‘acceleration-deceleration’ concept are really variations on Bunn’s definition. In essence, the principle states that, to produce the largest possible speed at the end of a linked chain of segments, the motion should start with the more proximal segments and proceed to the more distal segments. The more distal segment begins its motion at the time of the maximum speed of the proximal one, with each succeeding segment generating a larger endpoint velocity than the proximal segment.

Two- and three-dimensional kinematic analyses of throwing and striking activities are readily available in the literature (see, for example, Escamilla, et al., 1998; Sakurai et al., 1993; Woo and Chapman, 1994). Aspects of proximal-to-distal sequencing have been confirmed, although evaluation of individual segment contributions to hand or racquet speed and the role of long-axis rotations in temporal patterning have received little quantitative consideration.

In some activities, such as kicking a ball, neither segmental long axis rotation nor movement out of the primary plane appears to contribute significantly to the speed of the foot. On the other hand, movements such as throwing a ball or a forehand drive in squash are effective only if the skill takes advantage of movement about all the axes of rotation. An essential aspect of these skills is that the potential for rotation about each arm segment’s long axis is exploited so that maximum speed may be generated at the end of the kinematic chain.

However, an inspection of the literature suggests that there are aspects of throwing and striking activities where aberrations are seen in the traditional proximal-to-distal pattern. Feltner and Dapena (1986), Sakurai et al. (1993) and Woo and Chapman (1994) have all shown incidences in throwing or striking motions where internal rotation velocity of the upper arm reaches a maximum after the peak speeds of the forearm and hand segments. The peak velocity of pronation has also been reported to occur immediately before impact (Woo and Chapman, 1994; Sprigings et al., 1994), suggesting that this rotation also may not conform to traditional explanations of proximal-to-distal sequencing.

METHODS: Two-dimensional (usually sagittal plane) studies of segmental sequencing have typically ignored independent quantification of long axis rotations. Claims for segmental sequencing evidence have been based upon data from end-point (joint) speeds, segmental speeds, joint angular velocities and resultant joint moments (see, for example, Zernicke and Roberts, 1976; Joris et al., 1985; Kreighbaum and Barthels, 1985).
Several three-dimensional studies have also either ignored explicit quantification of long axis rotations or have calculated upper arm internal-external rotation from motion of the wrist relative to the long axis of the upper arm, a technique that works well until the elbow nears full extension. The closer the elbow is to full extension, the greater the error associated with this calculation (Feltner and Dapena, 1986; Vaughn, 1985; Fleisig et al., 1996).
Finally, several studies have quantified long axis rotation of the upper arm and forearm in throwing and striking skills by directly monitoring upper arm internal and external rotation and forearm pronation and supination (Elliott et al., 1995; Elliott et al., 1996; Elliott et al., 1997; Feltner and Nelson, 1996; Sakurai et al., 1993; Sprigings et al., 1994).

RESULTS: Results from eight studies reporting the timing and magnitude of upper arm internal rotation or pronation-supination speeds are summarised in Table 1. In all of these studies, one or both of the possible upper limb long-axis rotations reaches its peak speed at or near ball release or impact, and frequently after other shoulder and elbow rotations. These results confirm that long-axis rotations occur late in the sequencing of segmental motion in high-speed upper limb skills in contrast to a simplistic proximal-to-distal description.

Table 1 Timing and Magnitude of Long-axis Rotation Speeds in Throwing and Striking

Researchers	Activity	Upper arm internal rotation speed (IR)	Pronation-supination speed	Timing
Vaughn, 1985	Baseball pitchers	107 r/s		elbow extension, IR, release
Feltner & Dapena, 1986	Baseball pitchers	106 r/s		elbow extension, IR, release
Sakurai et al., 1993	Baseball pitchers		Pronation	pronation, [IR, wrist flexion and ulnar flexion], release
Barrentine et al., 1998	Baseball pitchers		Supination: 26 r/s	[ulnar deviation and wrist flexion], supination, release
Escamilla et al,. 1998	Baseball pitchers	80-105 r/s		horizontal abduction, elbow extension, IR, release
Feltner & Nelson, 1996	waterpolo throw	35 r/s	pronation: 20 r/s	pronation, IR, elbow extension, release
Elliott et al. 1995	Tennis serve	37 r/s	pronation: 15 r/s	[pronation and wrist flexion], IR, pronation, impact
Elliott et al. 1996	Squash forehand	52 r/s	pronation: 35 r/s	[IR, pronation and wrist flexion], impact

Table 1 shows a range of upper arm internal rotation speeds, which appear to increase with a decrease in the mass and moment of inertia of the object held in the hand. Although a reporting of the shoulder kinetics associated with these skills is beyond the scope of this paper, the magnitudes involved must signal a recognition of the importance as well as the potential dangers of upper arm internal rotation to these skills.
The pronation-supination speeds reported are lower than for upper arm internal rotation, but are still substantial. The difficulty in recording this motion may be inferred from the lack of data from baseball pitching studies.

Several studies have quantified the contribution of segment rotations to the speed of the hand or racquet. These are summarised in Table 2, where differences between a waterpolo throw and tennis or squash strokes can be seen. Internal rotation of the upper arm and wrist flexion are major contributors to racquet head speed; however, in a waterpolo penalty throw, trunk motion and elbow extension are the largest contributors. Presumably these differences are related to the magnitude of external forces available to the athlete as well as the mass and moment of inertia of the implement.

Table 2 Contribution of Long Axis Rotations to Hand or Racquet Head Speed

	% contribution to forward linear hand or racquet head speed			
	Water polo throw (Feltner & Nelson, 1996)	Tennis serve (Elliott et al., 1995)	Tennis forehands[1] (Elliott et al., 1997)	Squash forehand (Elliott et al., 1996)
Shoulder motion	29.1*	9.7	10.0 – 13.7	4.9
Upper arm IR	13.2	54.2	38.6 – 48.3	46.1
Elbow extension	26.6	-14.2	0.6 – 5.6	4.2
Pronation	-0.1	5.2	-0.6 – 4.6	12.0
Wrist flexion	4.8	30.6	1.1- 15.0	18.2

[1] ranges are from flat, topspin and lob forehands using two different grips
* combined trunk motion (4.9% anterioposterior + 24.2% trunk twist)

DISCUSSION: These studies provide quantitative information on the components of high velocity throws and racquet strokes, and confirm the importance of long-axis rotations (upper arm internal rotation and forearm pronation) in the development of speed. The concept of proximal-to-distal sequencing can now be more fully described, with the presentation of results that consistently show internal rotation of the upper arm and pronation occurring as some of the final components of the motion pattern. Data from these studies clearly show that attempts to explain proximal-to-distal segmental sequencing based upon two-dimensional information provide an incomplete description. While forearm pronation typically occurs after elbow extension and before, or simultaneous with, wrist flexion, the rotation that appears to differ from previous descriptions of proximal-to-distal sequencing is upper arm internal rotation. This movement occurs with, or after, wrist flexion in baseball pitching and racquet strokes, much later than predicted. The exception appears to be the waterpolo penalty throw where the specific and unique aspects of the skill require a modified sequencing. However, upper arm internal rotation still appears later in the sequence than would be predicted by a traditional proximal-to-distal description.
In addition, data from the studies quoted indicate the relative importance of these two long axis rotations. Upper arm internal rotation contributed between 38% and 54% of racquet head speed at impact and forearm pronation contributed between –0.6% and 12%, depending on racquet stroke. Unfortunately, data are not available on percentage contributions to ball speed for baseball pitching or football passing. In waterpolo it appears that long axis rotations are less important than might initially be expected.
This information suggests coaches and players should consider the range of motion, movement speed and timing of upper arm internal rotation in developing training regimes for strength, flexibility, speed and injury prevention.

CONCLUSIONS: It appears that most previous research examining the pattern of segmental sequencing in throwing and upper limb striking skills has simplified the movement by ignoring longitudinal axis motion. This has resulted in support for the proximal-to-distal sequence pattern as suggested by Bunn (1972) and others. Recent research indicates that, while there is a proximal-to-distal sequence in abduction-adduction and flexion-extension components of an upper limb skill, major contributions to the final speed of the hand or racquet result from longitudinal axis rotations. These results show internal rotation of the upper arm and pronation of the forearm frequently occurring as the final components of the motion pattern. Thus, this analysis also indicates traditional concepts of proximal-to-distal sequencing are inadequate to accurately describe the complexity of throwing and upper limb striking skills. It is essential to consider upper arm and forearm long axis rotations in explaining the mechanics of these movements as well as in developing coaching emphases, strength training schedules, and injury prevention programmes.

REFERENCES:

Barrentine, S.W., Matsuo, T., Escamilla, R.F., Fleisig, G.S., & Andrews, J.R. (1998). Kinematic analysis of the wrist and forearm during baseball pitching. *Journal of Applied Biomechanics,* **14**, 24-39.

Bunn, J. (1972). *Scientific Principles of Coaching*, Englewood Cliffs, NJ, Prentice-Hall, Inc.

Elliott, B., Marshall, R., & Noffal, G. (1995). Contributions of upper limb segment rotations during the power serve in tennis, *Journal of Applied Biomechanics,* **11**, 433-442.

Elliott, B., Marshall, R., & Noffal, G. (1996). The role of upper limb segment rotations in the development of racquet-head speed in the squash forehand, *Journal of Sports Sciences*, **14**, 159-165.

Elliott, B., Takahashi, K., & Noffal, G. (1997). The influence of grip position on upper limb contributions to racquet head velocity in a tennis forehand. *Journal of Applied Biomechanics,* **13**, 182-196.

Escamilla, R.F., Fleisig, G.S., Barrentine, S.W., Zheng, N., & Andrews, J.R. (1998). Kinematic comparisons of throwing different types of baseball pitches. *Journal of Applied Biomechanics,* **14**, 1-23.

Feltner, M.E., & Dapena, J. (1986). Dynamics of the shoulder and elbow joints of the throwing arm during a baseball pitch, *International Journal of Sport Biomechanics,* **2**, 235-259.

Feltner, M.E., & Nelson, S.T. (1996). Three-dimensional kinematics of the throwing arm during the penalty throw in water polo. *Journal of Applied Biomechanics,* **12**, 359-382.

Fleisig, G.S., Escamilla, R.F., Andrews, J.R., Matsuo, T., Satterwhite, Y., & Barrentine, S.W. (1996). Kinematic and kinetic comparison between baseball pitching and football passing. *Journal of Applied Biomechanics,* **12**, 207-224.

Joris, H.J., Edwards van Muyen, A.J., van Ingen Schenau, G.J., & Kemper, H.C. (1985). Force, velocity and energy flow during the overarm throw in female handball players. *Journal of Biomechanics,* **18**, 409-414.

Kreighbaum, E., & Barthels, K.M. (1985). *Biomechanics - a qualitative approach for studying human movement*. Burgess Publishing Co., Minneapolis.

Plagenhoef, S. (1971). *Patterns of Human Motion*. Prentice Hall, New Jersey.

Sakurai, S., Ikegami, Y., Okamoto, A., Yabe, K., & Toyoshima, S. (1993). A three-dimensional cinematographic analysis of upper limb movement during fastball and curveball baseball pitches. *Journal of Applied Biomechanics,* **9**, 45-65.

Sprigings, E., Marshall, R., Elliott, B., & Jennings, L. (1994). A three-dimensional kinematic method for determining the effectiveness of arm segment rotations in producing racquet-head speed. *Journal of Biomechanics,* **27**, 245-54.

Vaughn, R.E. (1985). An algorithm for determining arm action during overarm baseball pitches. In D.A. Winter, R.W. Norman, R.P. Wells, and A.E. Patla (Eds.), *Biomechanics IX-B* (pp. 510-515). Champaign, IL: Human Kinetics.

Woo, H., & Chapman, A.E. (1994). The temporal co-ordination of an elite squash forehand stroke. In *Proceedings of the Eighth Biennial Conference, Canadian Society for Biomechanics*, (pp. 230-1). Calgary: University of Calgary.

Zernicke, R.F., & Roberts E.M. (1976). Human lower extremity kinetic relationships during systematic variations in resultant limb velocity. In P.V. Komi (Ed.), *Biomechanics V-B* (pp. 20-25). Baltimore: University Park Press.