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The ontogeny of throwing and striking

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LIST OF ABBREVIATIONS

m	meter(s)
m/s	meters per second
msec	millisecond(s)
sec	second(s)
yrs	years

Abstract

Humans are the most adept throwers in the animal kingdom. Although throwing has been recorded in other primates, it is rare, weak, inaccurate and entails only arm movement. In contrast, human throwing is an explosive act employed from a bipedal stance that involves a complex, exceedingly rapid, full-body movement. This motion generates a pulse of kinetic energy in the legs that is progressively augmented by the pelvis, trunk, arm and hand, where it is transferred to a missile that is launched toward the target with high velocity and accuracy. Linking the study of throwing development in young children with analysis of the adult throwing motion makes it possible to address the question of whether human throwing is an acquired behavior or is based primarily on an inherited motor program. Current evidence supports the conclusion that the role of instruction and learning is minimal. Human throwing is predominantly the result of an innate motor program which emerges at a very early age in all children without teaching, yields a throwing motion that is the forerunner of the one used by adult athletes, is characterized by a prominent gender difference, and proceeds in some adults to a high level of proficiency. The same conclusions apparently apply also to striking (club-swinging), which employs a similar full-body motion. An explanation for these observations is presented, based upon the concept that throwing and club-swinging prowess provided reproductive advantages during early human evolution.

Introduction

Darwin (1871) was the first to call attention to the remarkable ability of our species to throw with speed and accuracy. "To throw a stone with as true an aim as can a Fuegian in defending himself, or in killing birds," he wrote, "requires the most consummate perfection in the correlated action of the muscles of the hand, arm, and shoulder, not to mention a fine sense of touch" (1871, p. 138). Such behavior is rarely recorded in other primates, and when observed it is ineffective. Darwin associated human throwing prowess with a distinctive body structure. The hands and arms could hardly have become perfect enough to have hurled stones and spears with a true aim, he believed, as long as they were habitually used for locomotion, body support, or climbing trees; furthermore, the successful thrower must stand firmly on his feet in an upright, bipedal stance. Today, Darwin's conclusions are thoroughly documented. Modern human adults are indeed the most effective throwers by a wide margin, a generalization that can be expanded to include the related behavior of swinging clubs. In their highest development, both motor skills employ a rapid, coordinated sequence of muscle contractions that begins in the legs and traverses the body, progressively accumulating kinetic energy that ultimately is transmitted to the hand, which then projects the missile or club towards a target.

Is this behavior inherited or learned? Is it based upon an innate ontogenetic process or is it a cultural product dependent upon teaching or other societal factors? This topic has yet to be examined. The following analysis of the development of throwing behavior in young children and its manifestation in adult athletes indicates that there is an inherited motor pattern that emerges shortly after birth in all children, yields a single type of bipedal throwing motion, is characterized by a gender disparity, involves remarkable complexity and rapidity, and reaches its highest level in a relatively small number of elite athletes, most of whom are males. These regularities suggest the possibility of an explanation based on natural selection during human evolution.

Development and maturation of throwing

Early studies. The earliest investigation of the development of throwing in children was described by Wild (1938). Thirty-two right-handed children from Iowa between the ages of 2 and 12 years were filmed while performing overhand throws. Wild measured 43 movement and nine timing features from which she reduced throwing development to four stages according to age. This pioneering research had a great and enduring impact on the field of science it created *(Wickstrom 1977)*. In Stage I, Wild reported, children ages 2-3 yrs threw from an upright stance with a simple arm movement. The flexed arm was moved high above the shoulder, with trunk extended, the body facing forward. The trunk flexed forward as the elbow extended and the arm swung over the shoulder and down in front. In Stage II, ages 3.5 to 5 yrs, a horizontal rotation was introduced. With feet remaining together in place, the body rotated right, then back to the left as the flexed right arm extended and swung forward. Stage III (ages 5-6) added a step, but often it was the right foot that moved forward with the throw. Stage IV (boys 6.5 yrs and older and a few girls) incorporated a weight shift to the right foot as the trunk rotated rightward and the throwing arm was swung upward and back, followed by a forward step shifting weight to the left foot, accompanied by forward trunk rotation, horizontal adduction of the throwing arm and extension at the elbow. Most girls displayed the body and foot movements, but less advanced arm movements. Some showed regressions. In another early study, H. Halverson (1940) found that the child first throws from a sitting posture before being able to stand, then throws bipedally when verticle balance is attained. Boys were found to be superior to girls in delivery, accuracy and distance thrown by 3.5-5 years of age. These pioneering reports showed that throwing behavior began shortly after birth and thereafter became more complex as it grew to resemble a rudimentary version of the motion employed by mature athletes (Figures 1 and 2).

Confirmation of throwing development and gender disparity. The emergence of a standardized overarm throwing motion has proved to be a feature of child development wherever it has been studied. Its ubiquity, early onset, age-related improvement, and the gender difference in its development have been confirmed in Japan *(Sakurai & Miyashita 1983)*, Tasmania *(Cooley et al. 1997)*, England *(Marques-Bruna & Grimshaw 1997)*, Brazil *(Teixeira & Gasparetto 2002)*, Germany *(Ehl et al. 2005)*, Senegal *(Bénéfice et al. 1999; Bénéfice & Malina 1996)*, Nigeria *(Toriola & Igbokwe 1986)*, Mexico *(Malina & Buschang 1985)*, New Guinea *(Malina et al. 1987)* and in many samples of children in the United States (*Keogh 1965; Malina et al. 1987; Morris et al. 1982; Wickstrom 1977*; and others cited below).

The conclusion that throwing develops naturally in all human children gains support from studies which show that children under the age of 3 *(H. Halverson 1940; Marques-Bruna & Grimshaw 1997; Wild 1938)* and preschoolers, ages 3-5 yrs from diverse cultures and ethnic groups, such as white children from Arizona *(Morris et al. 1982)* and black children from Nigeria *(Toriola & Igbokwe 1986)* are all able to throw. Even undernourished children, with reduced body size that adversely affects their throwing performance, show

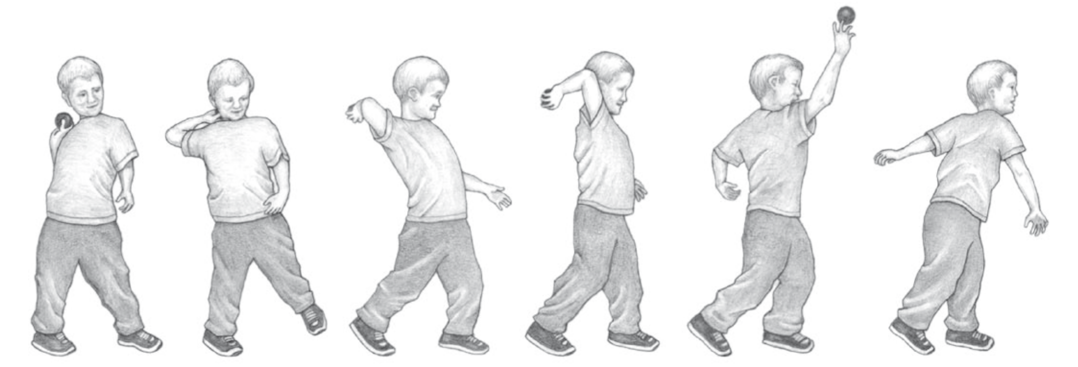

FIG. 1:
The throwing motion in a 4-year-old boy, drawn from photographs. Without prior instruction or training, the child uses a rudimentary version of the same throwing motion used by the adult athlete (shown in figure 2). The windup, step with weight shift (usually first seen in boys 5-6 yrs old), hip and torso rotation, forearm lag, elbow extension, overarm release and follow-through are all present.

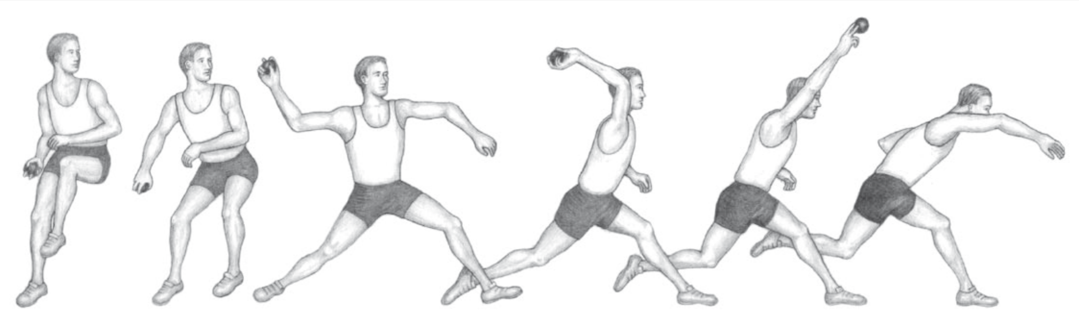

FIG. 2:
Drawing of the throwing motion in a mature, skilled thrower. Although throwing behavior appears in all children early in life, its development is variable. In only a relatively small proportion of individuals, primarily males, does it progress to the stage shown here.

an age-related increase in skill and a gender disparity *(Bénéfice et al. 1999; Bénéfice & Malina 1996; Malina & Buschang 1985; Malina et al. 1987)*. There are no reports of unusual throwing styles in any study sample. Wickstrom *(1977)* concluded that the overhand one-handed throw is the natural throwing pattern.

Development of throwing skill is variable. Roberton *(1977)* initiated the analysis of different body components during childhood development of throwing. This approach revealed variation of individual pathways *(Roberton & Langendorfer 1980)*. It also disclosed refinements in the throwing motion that appear late in development, including rotation of hips before shoulders, humerus motion after that of the shoulders, and forearm lagging behind humerus *(Halverson et al. 1982)*. In some individuals, development stops before these late refinements are installed *(Atwater 1979; Leme & Shambes 1978; Williams et al. 1998)*. This occurs more frequently in girls.

The developmental gender difference in throwing. From infancy through childhood the average performance of boys exceeds that of girls *(Wickstrom 1977)*. The magnitude of the difference in development of distance throwing between boys and girls exceeds that in any other motor skill *(Espenschade 1960)*. Gender differences detected at age 3 are already three times larger than in other motor behaviors *(Roberton & Langendorfer 1980; Thomas & French 1985)*. Keogh *(1965)* found that boys age 8 could throw farther than girls age 11. Similarly, boys in Grade 1 threw faster and farther than girls in grade 4 *(Rippee et al. 1990)*, and boys in grade 2 had a more advanced throwing motion than girls in grade 5 *(Butterfield & Loovis 1993)*. In a 1979 investigation of 13-year-old children from Wisconsin, boys threw on average 6.6 m/s faster than the girls *(Halverson et al. 1982)*. In 1999, the same research team *(Pulito Runion et al. 2003)* studied a matching sample from Ohio. The ball velocities and between-sex differences had not changed during 20 years. Next, the researchers applied the study protocol to 13-year-old German youths with different cultural influences *(Ehl et al. 2005)*. In Germany, many more youths play soccer than any throwing sport, a contrast to the emphasis on baseball and softball in the US. Although the US youths threw faster, the disparity between boys and girls in throwing velocity was identical in Germany and the US (6.9 m/sec) – comparable to the two US cohorts separated by 20 years. Keogh *(1965)* studied the throw for accuracy in 337 children ages 7-9 years. He recorded an improvement with age and a superiority of boys over girls at each age, even though boys threw from 1.5 m farther from the target. Among 960 children 6-9 years of age, there was annual improvement in throwing for accuracy and boys were significantly better than the girls at each age *(Wickstrom 1977)*. Other studies have also reported that boys outperform girls in tests of accuracy *(Hicks 1958; Rippee et al. 1990; Thomas & French 1985)*.

What causes childhood gender differences in throwing? There is no gender disparity in either static or dynamic balance *(Butterfield & Loovis 1993, 1998; Keogh 1965; Morris et al. 1982; Thomas & French 1985; Ulrich & Ulrich 1985)*. Physical factors are not likely to be involved. Gender sameness prior to puberty is the rule in body type, composition, strength, limb lengths, height and weight *(Bénéfice et al. 1999; Keogh 1965; Thomas & French 1985; Thomas 2000; Thomas et al. 2001; Toriola & Igbokwe 1986)*. Nor is there any known physiological, anatomical or maturational basis to account for the gender difference *(Butterfield & Loovis 1993, 1998; Nelson et al. 1986, 1991)*. It is not until puberty that numerous changes occur which accentuate the pre-existing male advantage. The notion that societal factors are important has often been proposed. Gender differences might be due to the different treatment society has for boys and girls, induced by parents, peers, teachers and coaches, rearing factors, cultural expectations, experiential differences, motivation, effort, encouragement and opportunities for training and skill development *(Butterfield & Loovis 1998; Espenschade 1960; Nelson et al. 1991; Sakurai & Miyashita 1983; Thomas et al. 1994; Thomas et al. 2001; Thomas & French 1985; Thomas & Thomas 1988; Ulrich & Ulrich 1985)*. Practice is considered essential to learning complex motor skills. In several studies boys reported more throwing than did girls *(Butterfield & Loovis 1998; Ehl et al. 2005; Halverson et al. 1982; Pulito Runion et al. 2003)*. In others, girls participated in youth sports at rates comparable to those of boys *(Butterfield & Loovis 1993)* and more advanced throwing patterns occurred in children of both sexes who participated in throwing sports *(Butterfield et al. 2003)*.

Instruction seems to make little difference in outcome scores such as distance or release velocity *(Dusenberry 1952)*. Halverson and colleagues *(1977)* studied children in kindergarten. Eight weeks of guided practice in the overhand throw did not significantly change the ball velocities of those who received it compared to those without it. The instructed group improved in the form of the throw, but not the velocity *(Halverson & Roberton 1979)*. Similarly, when young children were trained in throwing for 6 weeks, girls learned to mimic some aspects of a more advanced motion but without increasing the distance they could throw *(Thomas et al. 1994)*. Children who completed a teaching program in kindergarten showed no evidence of learning from instruction when re-examined at the close of first and second grade *(Roberton et al. 1979)*. Do young girls trained in throwing "catch up" with the boys? Thomas and coworkers *(1994)*, who reviewed investigations that dealt with this question in children ages 5-8 yrs, found there was no catch-up effect for girls. Gender differences appear to be resistant to instructional training in young children *(Thomas 2000)*, although practice seems likely to assist in throwing development *(Langendorfer & Roberton 2002)*. Throwing by older individuals may be improved by practice, strength and flexibility training, and slight adjustments of mechanical factors under the guidance of knowledgeable instructors *(Stodden et al. 2005)*. As much as 5% of the velocity difference between elite Korean and American adult throwers might be due to such factors *(Escamilla et al. 2002)*. However, evidence is lacking that such interventions affect the development of this skill in young children.

Two motions or one? Thomas and Marzke 's study of two adult throwers *(1992)* implied that there might be two distinct, gender-related, throwing motions *(Thomas et al. 2001)*. However, the view that in children there is a single motion, which does not develop as rapidly or completely in girls, is supported by much evidence. Girls appear to follow the same sequence of development but tend to lag behind boys in its progress *(Halverson et al. 1982; Nelson et al. 1986, 1991; Roberton & Langendorfer 1980; Seefeldt & Haubenstricker 1982)*. In one investigation, girls' throwing development trailed that of boys, but increased at the same rate *(Butterfield et al. 2003)*. In most studies, however, girls fall farther behind each year *(Espenschade 1960; Halverson et al. 1982; Keogh 1965; Roberton et al. 1979; Roberton & Konczak 2001; Teixeira & Gasparetto 2002; Thomas & French 1985)* and their progress may terminate earlier *(Butterfield & Loovis 1998; Nelson et al. 1991; Rippee et al. 1990; Roberton & Konczak 2001; Sakurai & Miyashita 1983)*.

The throwing motion that develops in children is a precursor of the one used by mature athletes. Investigation of throwing development by analysis of the movements of body components has been integrated with the analysis of throwing biomechanics in adult athletes by a team of researchers from both fields who studied 34 boys and 15 girls, 3 to 15 years of age *(Stodden et al. 2006a, b)*. Kinematic variables and developmental movement patterns (step, trunk, humerus and forearm actions) were positively correlated. Kinematics correctly predicted developmental levels 85% to 96% of the time. As developmental levels advanced, kinematic movements more closely resembled characteristics of elite throwers (Stodden et al. 2006a, b). By combining the genders, the researchers implicitly added support to the view that males and females follow the same developmental program, while the tabulated results (in which girls predominated at lower developmental levels and boys at higher ones) illustrate the gender disparity in throwing. Some children, mostly boys, complete the full developmental sequence at an early age (9-10 yrs). In studies of US throwers, Cosgarea et al. *(1993)* analyzed male baseball pitchers in four groups (9-12 yrs, 13-16 yrs, collegiate and professional). The kinematics of throwing were similar in all groups, although ball velocity increased with level of competition, most likely due to greater size and muscle strength. Fleisig and coworkers *(1999)* studied groups of males from youth (age 10-15 yrs) to professional. Again, velocity of the throw increased at each level, but there was no difference in the throwing motion. Subsequent studies of male baseball pitchers ages 9-12 yrs *(Fleisig et al. 2006)* further supported these conclusions.

The throwing motion in mature athletes. In expert throwers, movement begins with a runup (javelin) or windup (baseball pitching). The right-handed baseball pitch (a mirror image of the left-handed version) begins with the head facing the target, body turned to the right and leaning rearward, left leg raised, throwing arm directed backward with elbow extended (Figure 2). The partially flexed right leg then suddenly extends, thrusting the foot backward and downward into the ground, producing a reaction force and a forward weight shift. The left knee extends and the thigh rotates externally so that the foot points towards the target. As the foot strikes the ground, the knee flexes slightly, then extends, pushing backward, converting forward motion to rotatory motion around the long axis of the body *(Escamilla et al. 2002; Mero et al. 1994)*. Backward force against the left side of the pelvis causes the right side (thrust forward by the right leg) to accelerate, reinforced by the medial rotators of the hip joint. Sudden forward rotation of the right side of the hip produces a powerful stretch on the trunk. Now hip rotation decelerates and the trunk begins to rotate forward, aided by contraction of back and abdominal muscles *(Hirashima et al. 2002; Watkins et al. 1989)*. The left arm flexes at the elbow and moves closer to the body, accelerating trunk rotation *(Ishida & Hirano 2004)*. Suddenly, hip rotation is blocked facing the target, arrested by the external rotators at the hip joint. This transfers angular momentum to the torso, the right side of which swings forward with increasing velocity. When the shoulders near a position facing the target, rotation of the left side is blocked, producing an acceleration of the right side.

The arm, abducted and extended, now undergoes elbow flexion to about 90°. After the right shoulder has attained maximum velocity, movement of the right side of the torso decelerates, and the humerus rotates externally so that the hand gripping the ball is directed backwards. Just before maximum external rotation is attained (about 180°), elbow extension begins, then a powerful torque of medial rotation is applied to the humerus which whips the forearm forward *(Dillman et al. 1993; Matsuo et al. 2001; Werner et al. 1993)*. The hand lags behind, extending the wrist joint. Forward motion of the upper arm decelerates, accelerating the forearm and hand. When medial rotation reaches about 90°, the wrist flexes from extension to neutral, imparting additional thrust (Figure 2). The thumb drops away and the fingers extend at the moment of release *(Escamilla et al. 2002; MacWilliams et al. 1998; Matsuo et al. 2001; Sing 1984; Stodden et al. 2001; Tullos & King 1973; Wilk et al. 2000)*.

Escamilla and colleagues *(2001)* investigated 21 kinetic parameters in Olympic-level baseball pitchers from eight countries. Throwing kinematics were similar in all of them. Coaching, training and anthropometric features had no effect. Nor were there significant temporal differences between professional baseball pitchers from the US and Korea (*Escamilla et al. 2002)*. The same temporal sequencing was found in novice, club and elite javelin throwers *(Bartlett et al. 1996)*. Thus, the forceful throwing motion is essentially invariable for throwers of various standards and from different countries.

The rapidity of the throwing motion. Throwing is an explosive act. In baseball pitchers, after the windup, the time between front foot contact and ball release (Figure 2) is 145 msec *(Stodden et al. 2005)*. In a javelin throw the duration from final foot contact to release is similar *(Mero et al. 1994; Morriss & Bartlett 1996)*. The acceleration phase (when the missile moves towards the target until it is released) in a baseball throw lasts only 30-50 ms *(Stodden et al. 2005; Werner et al. 2001; Wilk et al. 2000)*. During this exceedingly brief interval, numerous independent muscle groups are successively activated and deactivated in a precisely coordinated manner under the control of the central nervous system (*See Gray et al. 2006; Hore et al. 1999, 2001, 2005a,* b; *Hore and Watts 2005; Timmann et al. 2008* for details and references).

Injury-prevention mechanisms. As the arm accelerates, internal rotation of the humerus occurs with such velocity that protective muscle reflexes have been built into the motion. Rotation is accompanied by axial compression which drives the humerus into the glenoid fossa, preventing distraction of the arm and doubling the stress that can be applied to the humerus without fracture *(Fleisig et al. 1995; Gainor et al. 1980)*. Innate mechanisms also protect the elbow. During acceleration, shoulder muscles bring the humerus forward, leaving the forearm and hand behind, putting stress on the medial side of the elbow joint. At that moment, an inward torque is applied by the forearm muscles to protect the ulnar collateral ligament *(Fleisig et al. 1995; Tullos & King 1973; Werner et al. 1993)*, and at ball release a powerful proximal force is produced at the elbow joint by flexor contraction to prevent distraction from centrifugal force acting on the forearm *(Fleisig et al. 1995; Loftice et al. 2004)*.

Development and maturation of striking

Throwing and striking are comparable behaviors. The ontogeny of club-swinging (striking) has seldom been studied, but although data are few, they match that of throwing very closely. Striking in children under the age of 30 months resembles the early overarm throwing motion, an arm thrust restricted to the anteriorposterior plane *(Wickstrom 1977)*. Halverson and coworkers *(1973)* found that the action of the trunk is similar in early sidearm striking and overhand throwing. Trunk rotation develops first in the upper spine. Next, the pelvis and upper spine begin to rotate as a unit, then pelvis rotation precedes the rotation of the spine. Langendorfer *(1987)* developed a system for analyzing overarm striking, using the component system developed by Roberton *(1977)* for overarm throwing. Boys ranging in age from 1.3 to 10.3 years used a racquet to strike a ball suspended above head height. Development of movement sequences of the trunk, humerus, elbow, spine and pelvis was comparable to that seen in throwing development. After age 6 a weight shift and forward step was commonly observed. The result by age 8 was an overhand striking motion essentially the same as that used in the mature throwing motion (Figure 3). Overhead striking and throwing can be performed using similar biomechanical actions *(Langendorfer 1987)*.

Gender differences in striking. Seefeldt and Haubenstricker *(1982)* devised stages for the development of sidearm striking a ball with a bat, beginning with feet stationary, the arms swinging forward in a chopping motion and culminating in a step forward, followed by rotation of hips, spine and shoulders, elbow extension and hand pronation at ball contact. Boys passed through these stages more rapidly than girls. Gender differences were evident by 2.7 yrs and the disparity increased with age. Using the same stages, Ulrich and Ulrich *(1985)* found that at 3-5 yrs girls lagged behind boys, similar to the disparity in throwing in the same children. Development of sidearm striking in children ages 4-14 yrs was studied by Loovis and Butterfield *(1995; Butterfield & Loovis 1998)*, who also found a resemblance to that of throwing. The earliest stage was confined to arm action. Later developments, such as a forward step, a weight shift to the front foot and separation of the rotation of pelvis and trunk were displayed by many boys in kindergarten. In girls, development was slower. Tasmanian schoolgirls also scored lower than boys on tests of striking skill *(Cooley et al. 1997)*.

The club-swinging motion in adult athletes. The mature striking motion is similar in many respects to the throwing motion. As displayed in the right-handed swing of a baseball bat, the batter stands with eyes on the target, body facing at right angles. The hands grip the club and extend it backward. The left heel is lifted as the left knee turns inward, redistributing weight to the right foot, which is then thrust into the ground, shifting weight forward. The left foot stays in place or strides forward. When the foot plants, the leg extends at the knee, pushing the left hip backward, while the right side of the pelvis rotates forward, creating a rotation around the axis of the trunk. Then, as hip rotation is blocked, the shoulders rotate forwards, leaving the arms behind. This radially deviates the wrists and bat. As the shoulders turn towards the target, their movement decelerates rapidly. Shoulder and arm muscles now swing the arms forward. The elbows extend, aligning arms and bat; the wrists move ulnarly. They are stabilized at impact to deliver maximum kinetic energy *(Jorgensen 1994; Welch et al. 1995)*. The baseball club swing, like the throw, is very rapid. The time elapsed between onset of forward motion until ball contact is about 0.58 sec *(Welch et al. 1995)*.

Similarities in throwing and striking

The kinetic energy linkage mechanism. Both throwing and club-swinging use similar sequences of muscular contractions which generate kinetic energy that is transferred through the body from the lower limbs to the hand-held implement. (The two motions differ primarily in wrist movements and handgrips associated with throwing the missile or swinging the club without release). In both acts the forces of each contracting muscle group supplement those generated by muscles acting earlier and contribute to the acceleration of the next moving part. Velocity is raised by

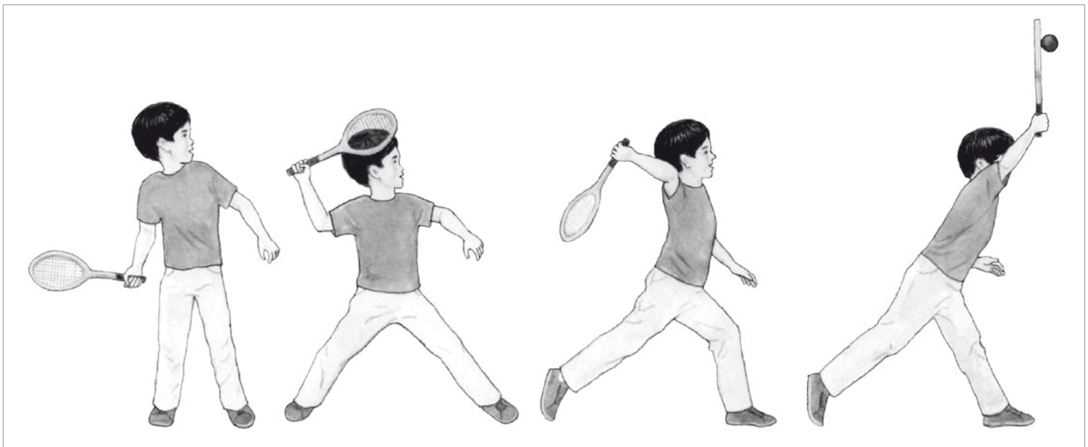

FIG. 3: Overhead striking by an 8-year old boy (adapted from Langendorfer, 1987). Note that apart from differences in handgrip and wrist movement the overhead striking motion is similar to the overhand throwing motion depicted in figures 1 and 2.

lengthening the acceleration path through which force is applied. This is the function of the windup, which coils the body before uncoiling it, activates stretch reflexes, optimizes length-tension conditions and stores recoverable elastic energy in tendons and ligaments *(Matsuo et al. 2001; Escamilla et al. 2002).* The generation of kinetic energy begins with the runup, or the thrust of the rear foot into the ground, initiating a weight shift towards the target. Lifting the left leg stores potential energy; extending it adds kinetic energy in the anterior direction. When the front foot plants and the knee extends, it produces a force couple – rear leg thrusting forward, front leg thrusting backward – accelerating the rotation of the pelvis, translating linear momentum into angular momentum. Then hip rotation is blocked, transferring momentum to the shoulders which, when their movement is terminated, pass the accumulating energy along the arm and hand to the sphere or club. As a general rule, each segment delays its motion until the maximum amount of energy can be transferred to it, linking the transfer of energy to parts of smaller mass moving at higher velocities *(Barrentine et al. 1998; Bartlett et al. 1996; Fleisig et al. 1996; Hore et al. 2005a; Kibler & McMullin 2003; Marshall & Elliott 2000; Stodden et al. 2005; Welch et al. 1995; Wilk et al. 2000).*

Gender differences in mature throwing and striking. Adult human females can throw and swing clubs with skill far exceeding that of either sex in any other species, but as a rule cannot match the prowess of human males at the elite level. World records indicate that women throw with about 60% of the power of men. In the tennis serve at the 2000 Olympics ball velocity of females was about 80% as fast as in males *(Fleisig et al. 2003).* Among Olympic javelin throwers, despite similar throwing motions, males outperform females *(Mero et al. 1994).* A gender disparity is also observed in professional golfers. Although the mechanics of the swing are similar, females drive the ball from the tee an average 15% shorter distance. Physical gender disparities in height, weight, strength and power might be involved *(Zheng et al. 2008).* Sex differences in body composition also may contribute to the adult male advantage in throwing and club-swinging *(Kirschmann 1999; Ransdell & Wells 1999).*

Discussion

The ontogeny of human throwing: Evidence of a genetic basis. Is human throwing and striking behavior inborn or acquired? Teaching, learning, practice and various societal influences may play a role, but the evidence indicates these factors are relatively insignificant in comparison to the genetic element. Throwing begins before children can stand and is subsequently performed from a bipedal stance. Instruction seems to have negligible effect on its early development. The throwing motion that develops in children is an elementary version of the one used by skilled, adult throwers. In some children the developmental program proceeds rapidly and goes to completion before puberty. In others, a rudimentary throwing motion may persist throughout life. A gender disparity is evident at an early age and increases as development proceeds. Girls often acquire this motor behavior at a slower pace and cease development at a lower level of skill. The club-swinging motion develops concurrently, with the same general features and gender difference. Elite throwers and clubbers from every part of the globe use the same motor program. There is no evidence that a more effective technique can be devised. Apparently, all humans inherit a tendency to develop the most biomechanically effective motion for throwing and striking. Furthermore, this action pattern is so complex and so rapid that it seems incompatible with a basis in learning at any age. Even in rudimentary form the throwing motion exceeds learning capacity in young children, yet its onset can be detected before 2 years after birth, gender differences are evident by 3 years, and this disparity is not reduced by teaching. Innate neuromuscular mechanisms act to prevent injury during forceful throwing. The multitude of coordinated body movements that occur during the acceleration phase in less than a second are further signs of a major genetic element.

A few authors have anticipated this viewpoint. Wild *(1938)* spoke of the "genetic history" of the throw. Others *(Thomas & French 1985; Thomas et al. 1994; Nelson et al. 1986; Butterfield & Loovis 1998; Butterfield et al. 2003)* have suggested that childhood gender differences in throwing may have a biological or hereditary component. Thomas and Marzke *(1992)*, Thomas *(2000)* and K. Thomas et al. *(2001)* raised the possibility that these effects may be rooted in an evolutionary process.

An evolutionary explanation. The predominantly inherited nature of the development of human throwing and striking does seem to require an evolutionary origin. If this motor behavior is part of the human ontogenetic program but is absent in other species, it must have arisen during our evolutionary history. It could have been incorporated into the human genome through natural selection of individuals whose prowess in these behaviors led to their leaving more offspring, thereby increasing the frequency of their genes in the breeding population. Our ancient ancestors may have enhanced their reproductive prospects by throwing stones and swinging clubs to gain an advantage over their competitors.

The use of weapons such as rocks and clubs to settle quarrels with fellow hominins and other animal species seems to offer numerous opportunities to improve reproductive success. Darwin *(1871)* suggested that throwing and club-swinging would have enabled human ancestors to defend themselves with stones or clubs, attack their prey or otherwise obtain food, and fight with their enemies. Those best constructed for this behavior, in Darwin's view, would have greater success and survival. Since then, many (over 40) authors have expressed the opinion that ancient hominins may have used weapons, such as stones for throwing and natural objects used as clubs. Isaac *(1987)* specifically linked throwing with human evolution. Kirschmann *(1999)* elaborated the idea that the human lineage arose when a population of apes began to throw stones at predators, and he identified several advantages associated with this behavior that could have led to a throwing adaptation.

The process of evolutionary adaptation is based upon natural selection which acts to enhance behaviors that promote reproductive success. The initial behavioral change and each subsequent stage in its improvement must provide a net reproductive advantage. If continued for an extended period, this process can result in the establishment of inherited attributes that augment the effectiveness of the behavior and increase the frequencies of the selected genes. The onset of aggressive use of rocks, sticks and bones as weapons could have yielded immediate reproductive advantages in a population of apes with no history of weapons use. It would have aided the rise of males in the dominance hierarchy *(Kirschmann 1999)*. The ancestral threat behavior of bluff and noise-making would have been ineffective against rivals wielding rocks or clubs. Enhanced ability to achieve high rank would increase access to food and females in estrus. In conflicts with outgroups, weapons would have provided advantages over males attempting to protect themselves, their females and their territory, increasing the availability of breeding females and food resources. Improved defense against predators would have aided survival *(Kirschmann 1999)*. Opportunities for scavenging would have increased when predators could be driven from carcasses. Weapons would have made hunting more efficient. Meat acquired by males could be traded for sex with females. Because males who were better throwers and strikers would have achieved higher ranks, wielded more power, controlled the best feeding sites, been better hunters and scavengers, and could protect women and children more effectively, females would have been more likely to select such males for mating, given the opportunity. Use of weapons would have enabled hominins to occupy safer habitats with more sources of shelter, water and food, promoting population growth and increasing the proportion of their genes in the breeding population.

Evolution of gender differences. This approach suggests an explanation for the gender disparity in the ontogeny and adult prowess of human throwing and clubbing behavior. Thomas and Marzke *(1992)* raised the possibility that gender disparities which appear during development of throwing, and the failure of training to reduce them, may suggest an evolutionary origin. They noted that some anatomical features that facilitate throwing appear early in evolution. Evolution could play a role in the development of gender differences if throwing was a valuable skill for species survival in males but not females and if selection for this skill had taken place *(Thomas 2000)*. Males, in contrast to females, were more likely to be hunters and warriors, resulting in greater reproductive selection for those who threw effectively *(Thomas et al. 2001)*. Selection that produced an innate advantage of males over females in throwing prowess presumably yielded greater reproductive advantages during evolution than gender parity. Females who devoted more resources to nurturing children and less to belligerent use of weapons may have been more successful in transmitting their genes to future generations. Modern human males are more active in fighting and hunting with weapons, whereas females may have less interest in these activities because of risk to dependent offspring and reproductive costs associated with pursuing dangerous, mobile prey. Furthermore, they may be pregnant or lactating *(Manson & Wrangham1991; Kaplan & Hill 1992; Tooby & DeVore 1986)*. This does not mean that aggressive use of rocks and clubs was of no benefit to early hominin females. Rather, it suggests they were less likely to engage in such behavior.

Evolutionary effect on the ontogenetic program. The reproductive advantages of throwing and club-swinging cited above are not applicable to small children. How can the onset of these behaviors in the very young be explained? Natural selection acts through differential reproduction, but puberty is preceded by several years of growth and development with implications for what follows. Children who developed the propensity and the skill for throwing and striking at an early age would be more likely to survive until puberty and to succeed in the competition for mates afterwards. The onset of such behavior in young children would provide a longer duration to develop these skills, supplying advantages later in life when it affected reproductive success.

Supporting evidence. Natural selection to promote throwing and clubbing prowess would lead to changes in any part of the body if the result was a net reproductive advantage. Two examples of related evidence will be briefly cited. The grip of a hand-held weapon would have been subject to selection. The fossil record reveals a process in which an ape-like early hominin hand with a short, weak, relatively immobile thumb and long, curved fingers was transformed into its current form, featuring a large, muscular opposable thumb and shorter, straight fingers. The functional result was two new grips: A fingertip-pad throwing grip for hurling spheroidal missiles, and a firm, buttressed striking grip for grasping cylindrical clubhandles *(Young 2003)*. The first signs of these changes are documented in *Ardipithecus kadabba,* nearly 6 million years ago, near the calculated time of hominin origins *(Haile-Selassie 2001; Semaw et al. 2005)*. Fossil evidence of changes in the canine teeth also indicate an early origin of adaptation to use of weapons in the human lineage. Most authorities have favored the view suggested by Darwin *(1871)* that the long, sharp-pointed canine teeth used by male anthropoids for threat and fighting diminished in size in the human lineage because these functions were replaced by weapons. The onset of this process also is evident in the fossil remains of *Ardipithecus kadabba (White et al. 2006; Haile-Selassie 2001; Haile-Selassie et al. 2004)*. Both trends continued until after the emergence of *Homo*.

Conclusion

Analysis of the ontological evidence of throwing behavior in humans indicates that it is dominated by a genetic element. Teaching, learning, practice and various other societal influences may play a role, but these factors prove to be less significant than the influence of biological inheritance. This generalization is based primarily on the following evidence: (1) Throwing behavior has been observed in young children of all cultures and ethnic groups that have been studied. (2) It begins very early in childhood, before vertical balance is possible. When upright stance is achieved, throwing becomes a bipedal act. (3) Instruction seems to have negligible effect on its early development. (4) A standardized throwing motion emerges which increasingly comes to resemble the one used by mature athletes. (5) In some children the developmental program proceeds rapidly and is completed before puberty. In others progress is slower and may terminate at an early stage. (6) Girls often acquire this motor behavior at a slower pace and complete development at a lower skill level. (7) A gender disparity favoring boys is evident as early as 3 years of age and subsequently increases. (8) This disparity is not reduced by teaching. (9) The striking (club-swinging) motion develops concurrently and with the same general features and gender difference. (10) The disparity persists in adults, enhanced by anatomical changes that occur at puberty. (11) Elite adult throwers throughout the world use the same throwing motion. (12) This motion appears to be the biomechanically most effective technique for throwing, given the structure of the human body. (13) Even in rudimentary form, it exceeds learning capacity in young children that display it. (14) In skilled athletes, most of the body 's musculoskeletal components contribute to throwing or striking in an explosive act lasting less than a second, accompanied by neuromuscular mechanisms which protect against injury from the associated high forces. (15) This motor behavior is so complex and so rapid that it seems incompatible with a basis in learning at any age.

The conclusion that genetic rather than societal factors predominate in the ontogeny of throwing and striking suggests that an evolutionary explanation might account for these behaviors. They may persist in modern humans because of events that occurred long ago during the evolution of our ancestors. Although throwing and striking seem to be of little use in the present era, they may have played an important role early in the human lineage. If they affected survival and reproductive success, these motor patterns could have been incorporated into the human genome through natural selection. Individuals who were adept at throwing and striking in ways that enabled them to produce more children would have increased the frequency of their genes in the breeding population. It is proposed that our ancient ancestors enhanced their reproductive prospects by throwing stones and swinging clubs to gain an advantage over their competitors in fighting and hunting. Fossil evidence suggests this trend may have begun near the onset of the human lineage. We seem to have inherited genes that were selected to enhance these behaviors over many thousands of generations beginning millions of years ago.

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