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RESEARCH ARTICLE

HEAD DEFLECTIONS DURING WALKING AND RUNNING

***Dr. Raymond H. Plaut**

D. H. Pletta Professor of Engineering (Emeritus), Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA 24061, U.S.A.

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ABSTRACT

Deflections of the head during level, straight, steady-state walking and running are considered. The literature is reviewed regarding the relationships between the forward speed, the step frequency, and the vertical, lateral, and fore-aft components of head motion for healthy adults. Typically: (i) the vertical amplitude of the head decreases as the speed of locomotion increases; (ii) the lateral amplitude increases as the speed of walking increases, reaches a maximum value in the jogging range (relatively slow running), and then decreases as the running speed increases; and (iii) the fore-aft amplitude (relative to the average forward motion) is small and does not vary significantly with speed. Based on the results presented in the literature, formulas are proposed for these three dynamic components of head motion.

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INTRODUCTION

During level, straight, steady-state walking or running, the deflections of a person's head possesses three oscillatory components. One is vertical, one is lateral (medial-lateral, sideways), and one is fore-aft (forward-backward, anterior-posterior) about the average speed in the direction of progression. During walking, the motion of the head in the coronal plane (frontal plane) that is perpendicular to the direction of progression forms a Lissajous figure, like a sideways (lazy) figure eight with the sides pushed upward. During running, the motion may resemble a thinner and taller U shape. Fore-aft motion exhibits a relatively small oscillation. Knowledge of the head motion may be useful in the development of devices such as implantable hearing systems, which could utilize this motion to provide energy for their operation (Goll *et al*., 2011). In the next section, the relationship between the average speed of walking or running and the step frequency will be described, and the walk-to-run and run-to-walk transitions will be discussed. In the following section, vertical and lateral motions of the head will be considered. Fore-aft motion of the head will be examined in the subsequent section, followed by conclusions.

****Corresponding author: Dr. Raymond H. Plaut***
D. H. Pletta Professor of Engineering (Emeritus), Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA 24061, U.S.A.

Vertical and lateral deflections during walking and running

Books that focus on the characteristics of human walking include Inman *et al*. (1981), Kirtley (2006), Perry and Burnfield (2010), Rose and Gamble (2006), Whittle (2007), and Winter (1991, 2009). General articles that discuss the kinematics of walking and/or running include Dicharry (2010), Dugan and Bhat (2005), Novacheck (1998), Vaughan (1984), and Williams (1985). Instruments used in clinical evaluation of gait kinematics are described in Surendar and Venguidaragavane (2013). The "step time" is the length of time between initial contact of one foot with the ground and subsequent initial contact of the other foot with the ground. The term "stride" sometimes refers to a step and sometimes refers to two consecutive steps, which can lead to confusion when comparing different studies in the literature. Because of this, the term "stride" will be avoided and the step rate f (i.e., the reciprocal of the step time) will be used. Sometimes f is called the cadence, especially if its units are steps per minute. Here, numerical values of f will be in steps per second (steps/s), which is often utilized in reported data. The average walking or running speed (sometimes called velocity) will be denoted V, with numerical values in m/s. Many papers have examined the relationship between f and V. A comparison of the differences on biomechanical behavior between running on a treadmill and "overground" running has been considered in a number of studies, e.g., Hirasaki *et al*. (1999), Murray *et al*.

(1985), Nelson *et al*. (1972), Van Caekenberghe *et al*. (2010a), Williams (1985), Yam *et al*. (2004), and Zanetti and Schieppatti (2007).With regard to the relationship $f(V)$ of the step frequency to the speed, the differences tend to be small and will be neglected here. It is noted that there is considerable variability in test results for biomechanical quantities associated with walking and running, such as step frequency, step length, and head motion; e.g., see Bollens *et al*. (2012), Dingwell and Cusumano (2010), Dingwell *et al*. (2010), Kao and Ringenbach (2004), Terrier *et al*. (2005), and Fig. 1. Standard deviations from mean values may be significant.

Step frequency during walking

For the walking range, a commonly used expression relating f and V has the form

$$f = \alpha\,(V/H)\beta \qquad (1)$$

where H is the height of the subject. (The ratio V/H is typically called the "relative speed" and denoted V', and H is often called the "stature" and denoted S.) Various combinations of values $\{\alpha, \beta\}$ have been proposed, based on mean values from experiments. For adult women, with f in steps/s and V/H in 1/s, the data from Grieve and Gear (1966) lead to $\{\alpha, \beta\}$ = {2.29, 0.61}for walking without shoes, Rosenrot *et al*. (1980) reported $\{\alpha, \beta\}$ = {2.22, 0.60} with shoes, Hirokawa (1989) obtained $\{\alpha, \beta\}$ = {2.44, 0.66} without shoes, Yamasaki *et al*. (1991) found $\{\alpha, \beta\}$ = {2.28, 0.53} with shoes, and Macellari *et al*. (1999) reported$\{\alpha, \beta\}$ = {2.13, 0.4} without shoes. Grieve and Gear (1966) claimed that the step frequency is 2-7% higher for walkers with shoes than without shoes. Some additional data for adult women can be found, for example, in Bertram and Ruina (2001), Chao *et al*. (1983), Dean (1965), Elliott and Blanksby (1979), Grieve (1968), Staszkiewicz *et al*. (2010), and Waters *et al*. (1988).For adult women wearing shoes, $\{\alpha, \beta\}$ = {2.4, 0.6} may be a good overall approximation, and with an assumed mean height of 1.63 m, this leads to

$$f = 1.8\ V^{0.6} \qquad (2)$$

with f in steps/s and V in m/s. For adult men wearing shoes, one could use $\{\alpha, \beta\}$ = {2.1, 0.5} with a mean height of 1.78 m, and then

$$f = 1.6\ V^{0.5} \qquad (3)$$

Transition between walking and running

As a person increases the speed of walking, he or she reaches the walk-to-run transition (WRT) and begins to run (i.e., to periodically have both feet off the ground). This transition has been discussed in many papers, including Alexander (2002), Beuter and Lalonde (1988), De Smet *et al*. (2009), Diedrich and Warren (1998), Hreljac (1993), Hreljac *et al*. (2007), Labini *et al*. (2011), Lamoth *et al*. (2009), Li (2000), Minetti *et al*. (1994), Ranisavljev *et al*. (2014), Segers *et al*. (2007), Sentija *et al*. (2012), Thorstensson and Roberthson (1987), and Van Caekenberghe *et al*. (2010a,b). A corresponding run-to-walk transition (RWT) occurs if the person is running and reduces speed sufficiently. The speed at which the RWT occurs is usually lower than that for the WRT, and this phenomenon is called "hysteresis"; e.g., see Diedrich and Warren (1998), Hreljac *et al*. (2007), Lamoth *et al*. (2009), Li (2000), Ranisavljev *et al*. (2014), and Turvey *et al*. (1999). Based on results in the literature, which contain quite a bit of variation, the WRT for a typical person tends to occur around V = 2.2 m/s (4.9 mph). According to some studies, e.g., De Smet *et al*. (2009), Diedrich and Warren (1998), Minetti *et al*. (1994), and Van Caekenberghe *et al*. (2010a), the WRT is accompanied by a sudden jump to a higher speed V and lower step frequency f. For example, in a study of 19 women reported in Van Caekenberghe *et al*. (2010a), mean values during the WRT were as follows: for running on a treadmill, V increased from 2.21 to 2.61 m/s while f decreased from 2.38 to 2.25 steps/s; for overground running, V increased from 2.34 to 2.85 m/s while f decreased from 2.41 to 2.22 steps/s.

Step frequency during running

For the running range, curves depicting the relationship $f(V)$ for men have been presented in Cavagna *et al*. (1991), Dillman (1975), Fukunaga *et al*. (1980), and Luhtanen and Komi (1978). Additional data are listed in Cavanagh and Kram (1989) and Nelson *et al*. (1972) for men, Elliott and Blanksby (1979) and Nelson *et al*. (1977) for men and women, and Teeple (1968) for women. The test results in Teeple (1968) for 28 women at three speeds each, ranging from V = 3.5 to 7.9 m/s, are presented in Fig. 1, along with a quadratic curve derived with the method of least squares. The curve is slightly concave downward, unlike the convex curves for men in Cavagna *et al*. (1991), Dillman (1975), Fukunaga *et al*. (1980), and Luhtanen and Komi (1978). Its formula is given by

$$f = 1.2 + 0.54V - 0.015\ V^2 \qquad (4)$$

with f in steps/s and V in m/s. A quadratic that approximates the mean values in the literature for men is

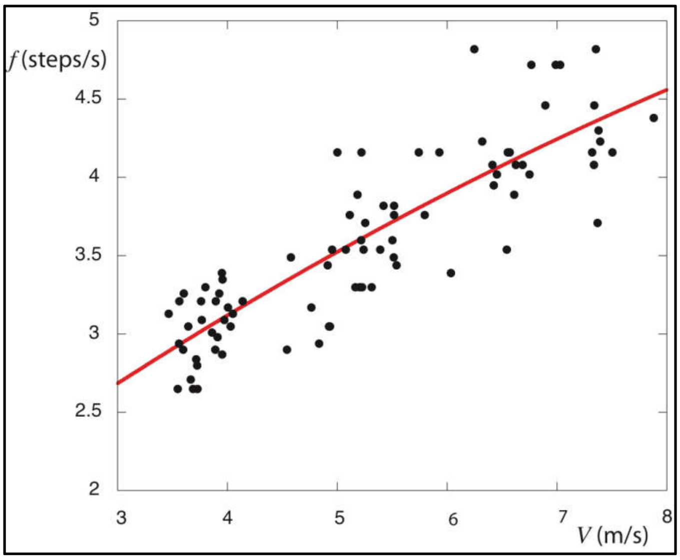

Fig. 1. Step frequency as a function of running speed; data from Teeple (1968), and quadratic curve

$$f = 2.73 - 0.077\ V + 0.024\ V^2 \qquad (5)$$

Nelson *et al*. (1977) presented data for men and women in the range 4.8 m/s $<V<$ 6.8 m/s. The mean frequencies for women were typically 0.14 steps/s higher than those for men. At a given running speed, women tend to have a smaller step length than men, and hence require a higher step frequency (Racic *et al*., 2009; Yamasaki *et al*., 1991). The 21 women tested in Nelson *et al*. (1977) were elite runners, and their step frequencies are close to the lowest data points in Fig. 1. In Elliott and Blanksby (1979), the mean data points for 10 non-competitive women runners at V= 2.5, 3.5, 4.5, and 5.5 m/s are, respectively, 9% higher, 1% lower, 6% lower, and 7% lower than the corresponding value given by Eq. (4). In Fig. 2, the curve given by Eq. (2) is plotted for $0 \le V \le 2.5$ m/s, and the curve defined by Eq. (4) is plotted for 1.8 m/s $\le V \le$ 9 m/s. The upper end point of the first curve is chosen to include most of the range of reported data for the WRT, and the lower end point of the second curve is below most of the data for the RWT.

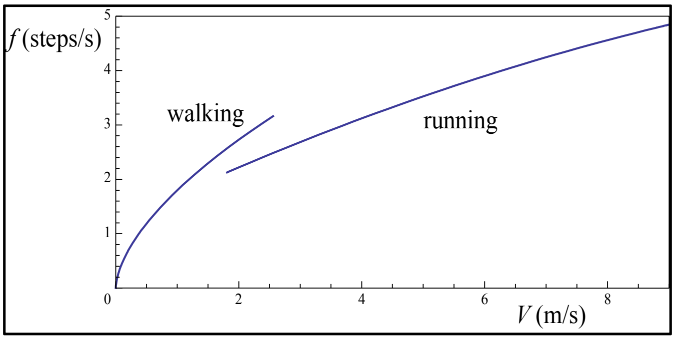

Fig. 2. Step frequency as a function of walking speed from Eq. (2) and running speed from Eq. (4)

Vertical and lateral head deflections

Deflections at the center of the back of the head are considered. At that location, the total horizontal (lateral) excursion in the coronal plane will be denoted $2A$, and the total vertical excursion will be $2B$. Data and plots have been reported in a number of papers. The walking range will be considered first. Murray *et al*. (1970) tested 30 women walking at a comfortable speed (free walking) and also as fast as possible (fast walking). For free and fast walking, respectively, the mean values of $2A$ were about 3.6 and 3.0 cm, and for $2B$ they were about 4.4 and 5 cm. For five male subjects, Waters *et al*. (1973) reported values of $2A$ as 5.0 and 5.4 cm for V = 1.22 and 1.62 m/s, respectively, and values of $2B$ as 2.6, 4.0, and 4.8 cm at V = 0.81, 1.22, and 1.62 m/s, respectively. Cappozzo (1981) tested five men. For slow walking, $2A$ was about 6 cm and $2B$ was about 5 cm. As V increased, $2A$ decreased slightly and $2B$ increased slightly. For seven women, Murray *et al*. (1984) gathered data at V = 0.83, 1.42, and 1.92 m/s, and respectively found $2A$ to be about 4.2, 3.2, and 2.7 cm, and $2B$ to be about 2.8, 4.1, and 5.4 cm. For one subject, Hirasaki *et al*. (1999) obtained values of $2B$ approximately equal to 3, 5, and 8 cm, respectively, at V = 0.8, 1.4, and 2.0 m/s. Therefore, as the walking speed increases, all of these investigations except Waters *et al*. (1973) concluded that the lateral amplitude of the head decreases, and all found that the vertical amplitude of the head increases.

For running, Cavanagh *et al*. (1977) tested 22 men, of whom 14 were categorized as elite runners and eight as good runners. For V from 4.96 to 6.44 m/s, mean values of 7.6 and 8.0 cm were reported for the elite and good runners, respectively, for the vertical excursion of the center of gravity. Luhtanen and Komi (1978) tested six men at 40, 60, 80, and 100% of their maximum running speeds, and found mean values for the vertical excursion of the center of gravity to be 10.9, 8.6, 7.0, and 6.7 cm, respectively. Finally, nine men and one woman were tested by Pozzo *et al*. (1990), and $2B$ ranged from 7 cm to 16 cm. Functions are proposed here for A and B in terms of step frequency f. They are based on the results in the literature, with the characteristics that with increasing f, A should decrease and B should increase in the walking range, and both A and B could be expected to decrease slightly during running. The assumed functions are fourth-order polynomials given by

$$A = 3 + 0.03f - 0.65f^2 + 0.206f^3 - 0.0186f^4 \qquad (6)$$

$$B = 0.063 - 0.0217f + 1.08f^2 - 0.365f^3 + 0.033f^4 \qquad (7)$$

with f in steps/s and A and B in cm.

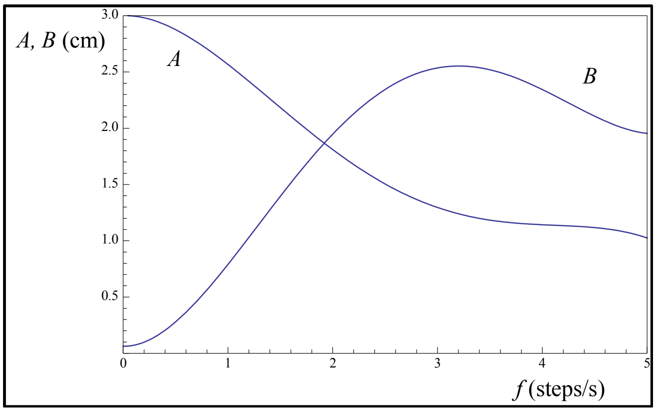

Fig. 3. Amplitudes *A* of lateral head motion from Eq. (6) and *B* of vertical head motion from Eq. (7) as functions of step frequency

These functions are plotted in Fig. 3 for $0 \le f \le 5$. The frequency f = 2.9 steps/s corresponds to the assumed walk-to-run transition speed of V = 2.2 m/s in Eq. (2), and the end value f = 5 steps/s corresponds to V = 9.6 m/s using Eq. (4). The functions are not necessarily accurate for very small values of f, but the effect of this in applications may be unimportant since head motions are small for very low walking speeds. Trajectories of the center of mass (CoM) of a human during walking are depicted in Tesio *et al*. (2010, 2011). The projection of the trajectory onto the coronal plane is shown in Tesio *et al*. (2010) and is a Lissajous figure. Similar figures are presented in Inman *et al*. (1981, 2006) and Orendurff *et al*. (1976) and for the CoM, in Gard *et al*. (1996) and Lamoreux (1971) for the pelvis, and in Cappozzo (1981) for the head, shoulders, and pelvis. Based on those studies, deflections of the head in the coronal plane are proposed here. Let and T denote time (in seconds), $X(T)$ the horizontal (lateral) motion (in cm), positive if to the right when viewing the back of the head and $Y(T)$ the vertical motion (in cm), positive if downward, and Ω the angular frequency for steps (in rad/s). The functions $X(T)$ and $Y(T)$ are chosen to be (Gard *et al*., 1996)

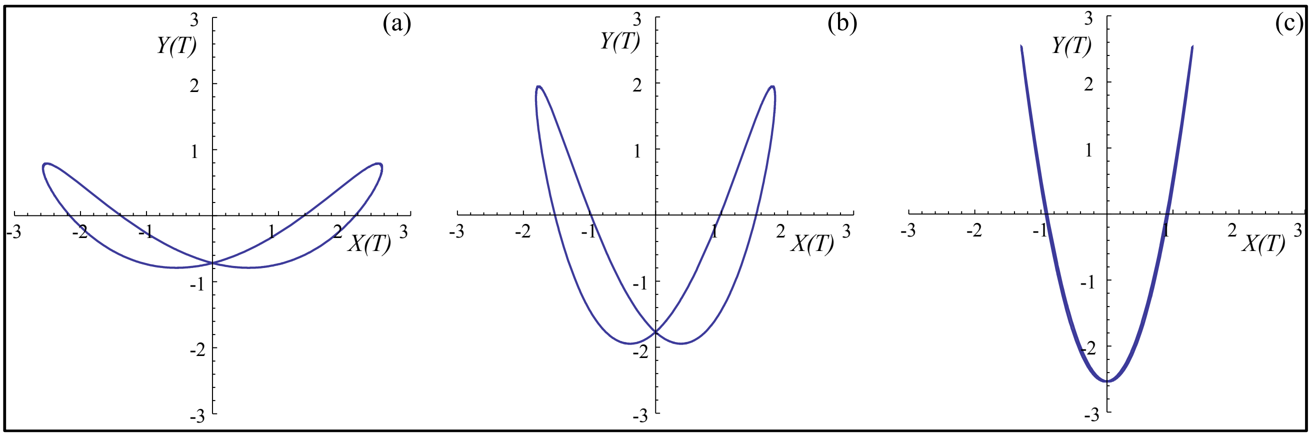

Fig. 4. Lissajous figures for projection of head motion in coronal plane for (a) $f = 1$ step/s, (b) $f = 2$ steps/s, and (c) $f = 3$ steps/s

$X(T) = A\sin(\Omega T + \beta)$, $Y(T) = -B\sin(2\Omega T)$ where $\Omega = \pi f$.(8)

The amplitudes A and B are given by Eqs. (6) and (7), respectively. The phase β is chosen to have the value 1 for $f \leq 2.9$ and 0.8 for $f > 2.9$. The vibration frequency for vertical motion (i.e., for steps) is twice that for lateral motion. The associated Lissajous figures are depicted in Figs. 4(a), (b), and (c) for $f = 1$, 2, and 3 steps/s, respectively. For walking ($f < 2.9$ steps/s), the shapes "resemble a slightly distorted lazy 8" (Inman *et al*., 1981, 2006). They become taller and thinner as the walking speed increases. For running ($f > 2.9$ steps/s), the shape is like a U, as seen in Fig. 4(c).

Fore-aft motion

During each step of steady-state walking or running, the forward speed varies with time. This variation has been neglected above, where only the average speed V was involved. However, it is included now in modeling fore-aft head motion. The forward speed is maximum close to the toe-off time when a foot leaves the ground (Herman *et al*., 1976). At that time, the vertical displacement of the head is almost at its minimum value (Cappozzo, 1991; Whittle, 2007).

In the fore-aft direction, it is proposed that the dynamic speed $V_{dyn}(T)$ of the head may be represented as

$$V_{dyn}(T) = V - 0.08\sin(2\pi f T) \quad (9)$$

in m/s, where V is the average speed as used previously. This choice is based on head velocities and/or accelerations reported in Cappozzo (1984,1991), Herman *et al*. (1976), Kavanagh *et al*. (2004), Mazza *et al*. (2008,2009), Menz *et al*. (2003), Waters *et al*. (1973), and Williams (1985). Most of the information in those studies applies to the walking range. It is noted in Cappozzo (1991) and Waters *et al*. (1973) that head accelerations in the fore-aft direction are much smaller than those at the pelvis and at the center of gravity of the body.

Forward motion of the head is obtained by integrating Eq. (9) with respect to time T.

Equations (2)-(5) can be used with V replaced by V_{dyn}, and Eqs. (6) and (7) are also applicable.

Conclusion

The deflections of a person's head during walking and running have been investigated. The head oscillates vertically and laterally, and also in the fore-aft direction about the average speed. Measured data in the literature demonstrate a large amount of variability in these head motions. Relationships between a healthy adult woman's and man's average speed of progression and the frequency of steps were proposed for the walking and running ranges, with discontinuities at the walk-to-run and run-to-walk transitions. Also, formulas for the vertical, lateral, and fore-aft deflections of the head as a function of step frequency were proposed. These formulas may be useful in various types of investigations involving human locomotion, and in applications such as energy harvesting.

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