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Short communication

The forces behind the words: Development of the Kinetic Pen

Alexander W. Hooke[a], Jaebum Park[a], Jae Kun Shim[a,b,c,*]

[a]*Department of Kinesiology, University of Maryland, College Park, MD 20742, USA*
[b]*Neuroscience and Cognitive Science Graduate Program, University of Maryland, College Park, MD 20742, USA*
[c]*The Graduate Program in Bioengineering, University of Maryland, College Park, MD 20742, USA*

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Abstract

This paper describes the creation of a Kinetic Pen capable of measuring the six-component force and torque that each of four individual contacts applies to the pen during writing. This was done by staggering the mounting of the four sensors along the long axis of the pen and having an extended arm run from the sensor to the grip site, preventing a clustering of the sensors where the digit tips meet while grasping. The implications of this tool allow handwriting studies to be expanded from two-dimensional pen-tip kinematics to three-dimensional dynamics at each contact point between the hand and pen.

Keywords: Handwriting; Kinetics; Force; Three dimensions; Motor control

1. Introduction

The ability to produce proficient and legible script is a skill necessary in everyday life for both children and adults. A lack of this skill leads to several undesirable effects such as misinterpretations due to illegibility, a negative influence of poor penmanship on a writer's perceived competence, and a lack of composition skills due to motor memory interference (Berninger et al., 1997; Graham et al., 2000; Peverly, 2006). Scripting ability can be easily affected by neurological disorders such as Parkinson's disease (Van Gemmert et al., 2001, 2003; Caligiuri et al., 2006), schizophrenia (Tigges et al., 2000), obsessive compulsive disorder (Mavrogiorgou et al., 2001), depression (Mergl et al., 2004), and others. Additionally, focal dystonias, such as writer's cramp, can have negative effects on writing ability and have a largely unknown pathogenesis (Sheehy and Marsden, 1982; Cohen and Hallett, 1988).

Previous research has primarily focused on the kinematic aspects of handwriting. However, this does not necessarily provide information on the unique kinetic relationships between the hand and pen. For example, when a system is kinetically redundant (Shim et al., 2005, 2007), as in the three-digit grasp often used in handwriting, different digit force and torque combinations can produce identical kinematic profiles. The inability to physically fit the necessary sensors into a natural grip setting has previously prevented this extension to kinetic handwriting research (Latash et al., 2003). Limited previous research on handwriting kinetics has focused on force relationships between the writing surface and pen-tip (Wann and Nimmo-Smith, 1991; van Den Heuvel et al., 1998), as well as one-dimensional grasping forces (Herrick and Otto, 1961). A more recent attempt at measuring pen grip forces investigated total grasping force as well as digit-force specificity via contour plots (Chau et al., 2006). Recording six-component signals (three force and torque components) from each contact during handwriting is critical in research on handwriting mechanics because handwriting occurs in three dimensions and cannot be simplified to less dimensionality.

2. Instrumentation

The dimensions of the Kinetic Pen are similar to those of a typical writing utensil (Fig. 1A).

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*Corresponding author at: University of Maryland, Kinesiology/Neuroscience and Cognitive Science/Bioengineering, 0110F HHP, College Park, MD 20742, USA. Tel.: +1 301 405 9240; fax: +1 301 405 5578.
E-mail address: jkshim@umd.edu (J.K. Shim).

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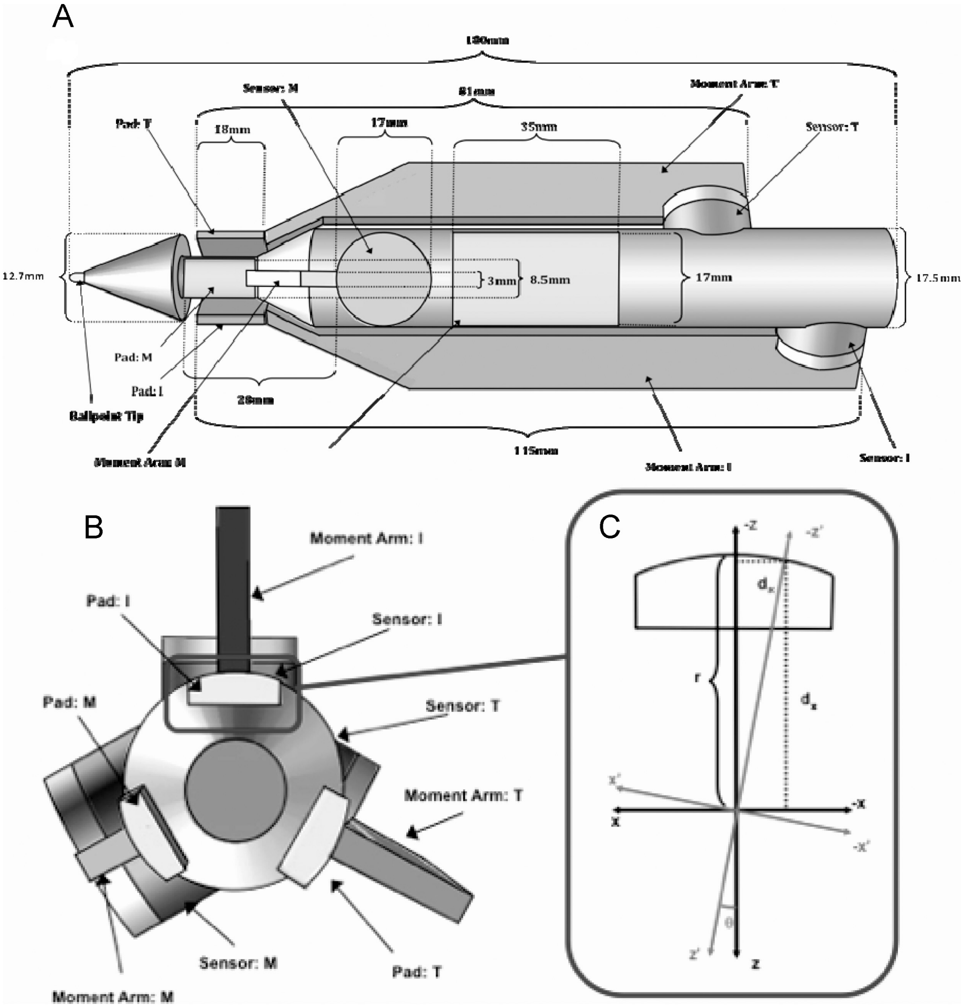

Fig. 1. (A) Schematic of Kinetic Pen with sensors, moment arms, and grip pads labeled by contact point. Units are mm and *T*, *I*, *M*, and *W* represent, thumb, index, middle, and webbing area, respectively. (B) Schematic of Kinetic Pen viewed from writing end with tip removed. (C) Definition of original x_j-and z_j-axis, transformed x_j'- and z_j'-axis, x_j- and z_j-moment arms (d_{xj} and d_{zj}), radius (r), and rotation angle (θ_j). y_j-axis is not shown in the figure, but it is orthogonal to x_j- and z_j-axis, and follows the right hand-thumb rule for its direction.

The pen is equipped with four, six-component sensors (Nano-17, ATI Industrial Automation, Garner, NC, USA). The manufacturer provided a calibration matrix calculated from a set of loading scenarios designed to cover the entire six-axis calibration range. These procedures comply with the ISO 9001 standard. The measurement uncertainty for the calibration ranged between 0.01% and 0.96%. The independent measures of each of the three-dimensional force and torque components were achieved by multiplying the sensor-specific calibration matrix by the six-channel analog signals.

Each sensor is countersunk into the pen's body such that all but 2 mm is encased and corresponds to an individual contact point with the hand in a typical, four contact-point writing grip: thumb, index finger, middle finger, and webbing between the thumb and index finger. Thumb, index and middle digits' sensors have extended arms mounted to the flat surface of their respective sensor and run parallel to the long axis of the pen ending at a rounded grip site. The extended arms contact the pen at exclusively their respective sensor mountings and nowhere else on the pen body. This "floating" design of the arms yields forces at the grip site to equivalent the sensor readings. The thumb and index finger's extended arms are titanium, eliminating arm bend. The shorter, middle finger arm is aluminum. The webbing sensor has an aluminum plate mounted to its surface as a resting pad that can be adjusted via translations along the pen's long axis to accommodate varying hand sizes. These attachments prevent temperature-sensitive signal distortions.

3. Reference system transformation

Each sensor uniquely corresponds to a specified contact point (*j*) with the pen and has its own original local reference system such that the *y*-axis runs parallel to the pen's long axis, the *x*-axis runs tangential to the curvature of the pen's body, and the *z*-axis passes through the pen's body, normal to the surface curvature (Fig. 1C). Each of the sensors has three component force ($\overrightarrow{F_j}$) and torque ($\overrightarrow{T_j}$) outputs. The total torque is comprised of force, moment arm ($\overrightarrow{d_j}$), and free torque ($\overrightarrow{\mu_j}$) elements (Eq. (1)):

$$\begin{aligned}\overrightarrow{T_j} &= \overrightarrow{d_j} \times \overrightarrow{F_j} + \overrightarrow{\mu_j}\\ \overrightarrow{F_j} &= [F_{xj}, F_{yj}, F_{zj}]\\ \overrightarrow{T_j} &= [T_{xj}, T_{yj}, T_{zj}]\\ \overrightarrow{d_j} &= [d_{xj}, d_{yj}, d_{zj}]\\ \overrightarrow{\mu_j} &= [\mu_{xj}, \mu_{yj}, \mu_{zj}](1)\end{aligned}$$

j is contact point of thumb index, middle or web area.

The center of pressure (COP) of each digit on the grip pad fluctuates during a writing task. To increase the intuitiveness of analysis, the original local coordinate systems (i.e., x–y–z) of each sensor are transformed via a center of pressure-determined y-axis rotation such that the rotated x'- and z'-axis represent the tangential and normal axes, respectively (Fig. 1C). The amount of rotation (θ_j) is unique to each contact at each moment in time and is described by rotation matrix $R_{\theta j}$ (Eq. (2)):

$$R_{\theta j}(t) = \begin{bmatrix} \cos(\theta_j(t)) & 0 & -\sin(\theta_j(t)) \\ 0 & 1 & 0 \\ \sin(\theta_j(t)) & 0 & \cos(\theta_j(t)) \end{bmatrix} \tag{2}$$

The forces ($\overrightarrow{F_j}'$), torques ($\overrightarrow{T_j}'$), moment arms ($\overrightarrow{d_j}'$), and free torques ($\overrightarrow{\mu_j}'$) in the transformed reference system (i.e., x'–y'–z') are calculated by multiplying the transformation matrix, $R_{\theta j}$, by each respective vector (Eq. (3)):

$$\begin{aligned}\overrightarrow{F_j}' &= R_{\theta j}\overrightarrow{F_j}\\ \overrightarrow{T_j}' &= R_{\theta j}\overrightarrow{T_j}\\ \overrightarrow{d_j}' &= R_{\theta j}\overrightarrow{d_j}\\ \overrightarrow{\mu_j}' &= R_{\theta j}\overrightarrow{\mu_j}\end{aligned} \tag{3}$$

The transformed force, torque, moment arm, and free torque values must be found as a function of the original force and torque components (as these are the sensor outputs) and distance r, representing the distance from the sensor origin to the surface of the grip pad (Fig. 1C).

The original moment arm values of d_{xj} and d_{zj} can be described in terms of the rotation angle θ_j and distance r, as illustrated in Fig. 1 (Eq. (4)):

$$\begin{aligned}d_{xj} &= -r\sin(\theta_j)\\ d_{zj} &= -r\cos(\theta_j)\end{aligned} \tag{4}$$

The original torque definition equation defined previously (Eq. (1)) is expanded and the d_{xj} and d_{zj} values in Eq. (4) can be substituted into the y-component of the total torque (Eq. (5)):

$$\begin{aligned}T_{yj} &= d_{zj}F_{xj} - d_{xj}F_{zj} + \mu_{yj}\\ T_{yj} &= r\sin(\theta_j)F_{zj} - r\cos(\theta_j)F_{xj} + \mu_{yj}\end{aligned} \tag{5}$$

No free torque about the y-axis exists because it has no normality with the grip site,

$$T_{yj} = r\sin(\theta_j)F_{zj} - r\cos(\theta_j)F_{xj} \tag{6}$$

The physical constraints of the grip pads dictate that range of possible θ_j values is $-45°$ to $45°$ (Fig. 1C). By solving Eq. (6) for θ_j, the amount of y-axis rotation needed to define the x'- and z'-axes as instantaneously tangential and normal to the grip pad, respectively, is a function of all known values (Eq. (7)):

$$\theta_j = \sin^{-1}\left(\frac{T_{yj}}{r\sqrt{F_{xj}^2 + F_{zj}^2}}\right) + \tan^{-1}\left(\frac{F_{xj}}{F_{zj}}\right) \tag{7}$$

Using the above equation (Eq. (7)), the transformed forces ($\overrightarrow{F_j}'$) and torques ($\overrightarrow{T_j}'$) can be calculated by substituting θ_j into the rotation matrix $R_{\theta j}$.

As the z'-axis is the only axis normal to the grip site in the transformed system, free torques about the x'- and y'-axis cannot exist, the tangential displacement of the moment arm (d'_{xj}) disappears, and the distance from the system origin to the grip site, —r, is equivalent to d'_{zj} (Eq. (8)).

$$\begin{aligned}\mu'_{xj} &= \mu'_{yj} = 0\\ d'_{xj} &= 0\\ d'_{zj} &= -r\end{aligned} \tag{8}$$

By substituting the values defined above (Eq. (8)) into the transformed component torque equations, the only remaining unknown values of d'_{yj} and μ'_{zj} can be found (Eq. (9)):

$$\begin{aligned}T'_{xj} &= d'_{yj}F'_{zj} + rF'_{yj}\\ T'_{yj} &= -rF'_{zj}\\ T'_{zj} &= -d'_{yj}F'_{xj} + \mu'_{zj}\end{aligned} \tag{9}$$

The T'_{xj} and T'_{zj} equations are used to solve for final unknowns, d'_{yj} and μ'_{zj} (Eq. (10)):

$$\begin{aligned}d'_y &= \frac{T'_x - rF'_y}{F'_z}\\ \mu'_z &= T'_z + \left(\frac{T'_x - rF'_y}{F'_z}\right)F'_x\end{aligned} \tag{10}$$

The $\overrightarrow{F_j}'$, $\overrightarrow{T_j}'$, $\overrightarrow{d_j}'$, and $\overrightarrow{\mu_j}'$ values are then known for each contact point on the pen and the relationships between these values can be identified instantaneously over time.

Fig. 2 shows a time profile of the transformed output of a single trial of a subject writing “Wordplay”. The initiation of each letter was determined by non-zero readings from a force plate writing surface and these points are indicated by vertical dashed lines. The transformations comply with the expectations based on the physical properties of the system as well as what specific forces are produced along each axis and how the orientation of the pen’s contact with the digits fluctuates during writing.

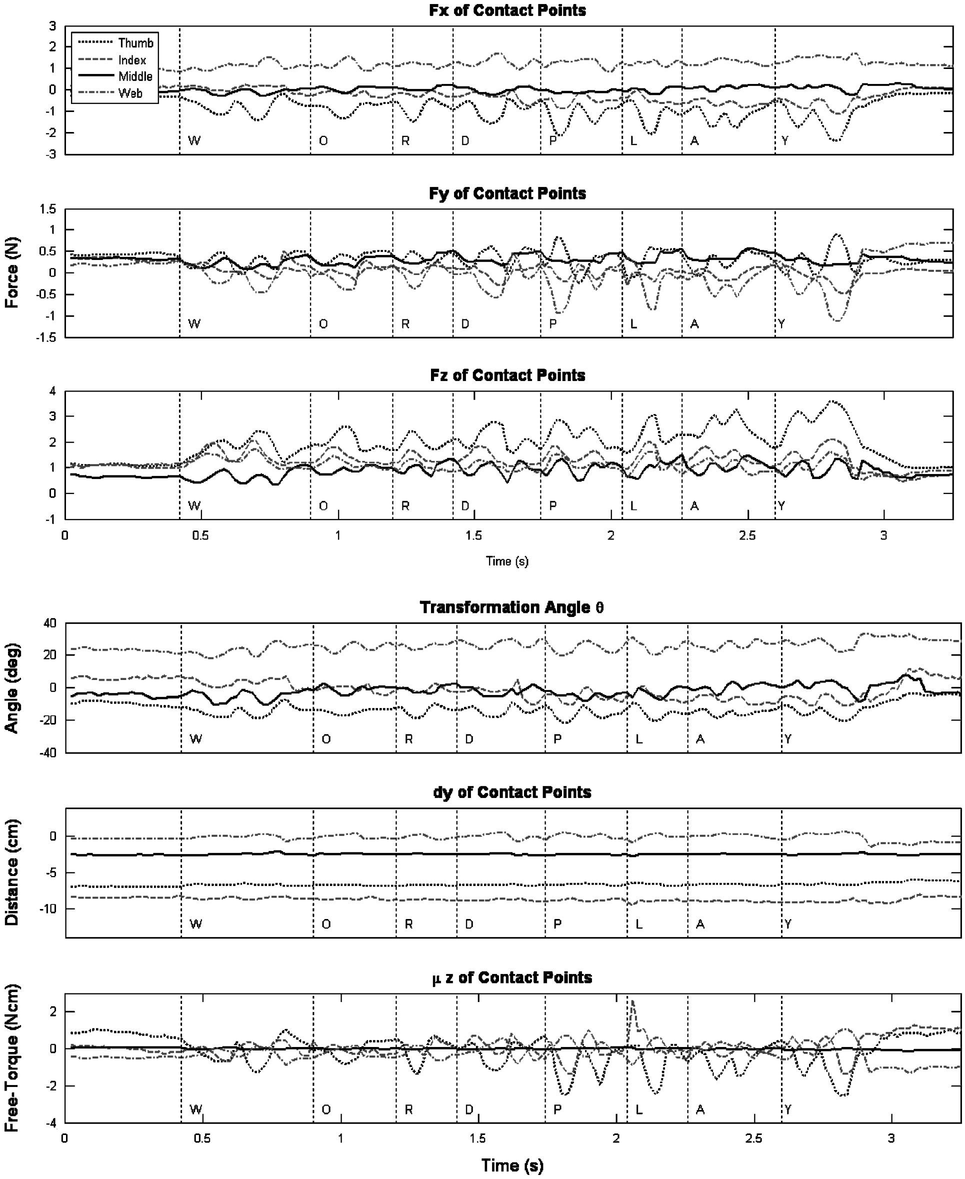

Fig. 2. Time profiles of a single trial of transformed data of a subject writing "Wordplay". The vertical dashed lines indicate the initiation of the writing of the corresponding letter. The thumb, index, middle, and webbing components are shown. (A) F_x': forces tangential to the curvature of the pen. (B) F_y': forces running parallel to the pen's long axis. (C) F_z': forces normal to the curvature of the pen (D) θ: transformation angle (E) d_y': distance along pen's long axis from sensor to grip site center of pressure (F) μ_z': free torque about axis normal to curvature of pen.

4. Implications

The Kinetic Pen provides three-dimensional forces and torques at each contact enabling researchers to quantify the finger joint torques from inverse dynamics during handwriting. This was not possible in previous studies (Wann and Nimmo-Smith, 1991; van Den Heuvel et al., 1998; Chau et al., 2006). This tool provides a novel set of measurement techniques in handwriting mechanics, shedding light on issues such as on the pathogenesis of writer's cramp and other focal dystonias (Sheehy and Marsden, 1982; Cohen and Hallett, 1988). Previous investigations on this have been limited to EMG of forearm muscles and neural imaging techniques that do not provide a comprehensive understanding of specific tendon and muscles forces (Cohen and Hallett, 1988; Tempel and Perlmutter, 1993; Müller and Poewe, 2007). These forces may be identifiable via inverse dynamics using this instrument. Our future studies will investigate the force and torque synergies of the digits during writing and the inverse dynamics of these relationships, offering help in the diagnoses, quantification and treatment of movement and psychological disorders and dystonias connected to handwriting.

Conflict of interest

There is no conflict of interest regarding our manuscript entitled "The forces behind the words: Development of the

Kinetic Pen'' that we want to submit to the Journal of Biomechanics as a Short Communication.

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