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Nonlinearities in Hand and Foot Coordination

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Abstract

Biomechanical studies performed over the past thirty years have demonstrated that the simultaneous motion of human appendages exhibits significant coordination or “synergy” and that this dependence of the motion of seemingly independent body extremities is highly nonlinear. The present paper reports new experimental research conducted with a group of subjects for the case of coupled hand and foot movements. In these experiments, a series of discrete synchronized hand-foot movement trials are performed. Subjects attempt to move one hand and one foot simultaneously from a start to target location (horizontal translation), while simultaneously moving one of these appendages (hand or foot) vertically to clear a barrier. In the experiments, the effects of right-left limb pairing, direction of movement in relation to the body and the placement of a path-obstructing barrier are investigated. To quantitatively study the phenomenon, data consisting of time histories of the moving limbs are digitally recorded, processed with a data reduction program and statistically analyzed. Results show that the effect of foot motion on the motion of the hand is greater than the corresponding effect of hand motion on the foot. Another nonlinearity is revealed in examining the velocity of these coordinated motions; i.e. the hand is observed to move with greater initial velocity than the foot, irrespective of whether it is clearing the obstacle or mimicking. This curious phenomenon is discussed in the paper together with the results of analysis of the other measured data.

Nonlinearities in Hand and Foot Coordination

Introduction

Coordination of the simultaneous motion of human appendages involves a complex interplay of the neurological and muscular systems. Control of the kinematics of such coordinated motion requires multiple feedback paths connecting the tactile sensors and muscle groups. Observations have revealed dramatic nonlinearities in these mechanisms. For example, hand motion occurring simultaneously with foot motion over an obstacle demonstrates involuntary action of the moving hand mimicking the obstacle clearance trajectory of the foot; while only a less drastic imitation seems to occur when the foot is moving simultaneously with an-obstacle avoiding hand. This research project examines these nonlinearities through a motor experiment study on a group of subjects. An in-depth computational analysis of the data measuring the kinematics associated with coordinated hand-foot motions provides insight on the coupling of movements.

Specifically, the objectives of the experiments are to investigate hand and foot coordinated motion and gather data relating to coupling between them. Statistical interpretation of the data substantiates a coordinative coupling phenomenon and provides evidence that the influence of the foot on the hand in a coupled motion is greater than that of the hand on the foot.

The rest of the paper is organized as follows. The next section entails a detailed literature review of past studies which examine kinematics and dynamics of motion, beginning with Kelso's study of bilateral coordination. Following that section, the methodology of the experiment is described, including an account of the participating subjects, a description of the experimental set-up and equipment, the procedure, data reduction and methods for analysis. The results are then presented and discussed, and possible explanations of the findings are proposed.

Literature Review

An important underlying concept in this experiment is that of synergy. This term describes the phenomenon of individual components of a system acting as a single unit to simplify a task. In this experiment, one sees that the hands and feet tend to act as a single commodity. These seemingly independent body extremities have an influence on one another's movement when performing simultaneous tasks.

Kelso, Southard, and Goodman's research article "On the Coordination of Two-Handed Movements" (1979), provides significant evidence that the brain organizes muscles into functional groupings or "coordinative structures" that tend to act together as one unit. Through a series of three experiments performed on multiple subjects, the idea of synergy between two hands emerged. In the first experiment 12 subjects were assigned a task to move their index fingers from a starting point outward to a target destination, on a horizontal plane, as fast and as accurately as possible. Several factors affected the experimental conditions: 1. whether the movement was one or two-handed, 2. the difficulty of the task determined by the size of the target, 3. whether a short or long distance was covered by the movement. For each trial, in each condition, the measurements taken were mean reaction time, movement time, and total response time for each hand. The time in which peak velocities and accelerations occurred was recorded as well. The results of the experiments showed that easy tasks were slower when paired with a more difficult task than they were when conducted with another easy task or alone.

The second experiment examined a similar set of conditions, the difference being that the initial and final points were interchanged, so the subjects moved their index fingers inward. The same difficulties were provided and the mean reaction time, movement time, and total response time were recorded for each trial. In agreement with the first experiment, it was noted that the difficult task performed in conjunction with the easy task seemed to determine the movement time. The easy task took longer when paired with the difficult task.

Whereas conditions of experiments 1 and 2 required the movement of symmetrical muscle groups in opposite directions, the third experiment examined movement of symmetrical muscle groups in the same direction. The two-handed movements of varying difficulty were performed in the forward direction, away from the subject. Once more, the influence of the difficult task on the paired easy task was significant. Temporal coordination was also revealed in all the trials through the remarkably similar trajectory shapes, starting times, times to peak acceleration, times to maximum height, etc. of the two hands. The results of the experiments imply that the upper bilateral extremities are controlled by coordinating coupling, (Kelso et al., 1979).

In 1991 Fowler et al. reproduced the findings of Kelso’s 1979 bimanual experiments. The procedures were the same as those used in the third experiment, with the addition of another, even more difficult condition. The results showed the same phenomena. An important discrepancy to note, however, is the fact that although the movement times for the easy tasks were slowed down, they always remained smaller than the times for the more difficult tasks. Since they never achieved perfect synchrony, it appears that rather than being strictly locked together, a “strong determining influence” was exerted by the limb performing the difficult task, (Schmidt 1999).

Goodman, Kobayashi and Kelso further investigated this phenomenon in 1983. They performed a study in which subjects moved both hands the same distance to identical targets, with a barrier obstructing the path of only one of the hands. As the height of the barrier was increased systematically from 0 cm to 40 cm, subsequent, steady increases of movement times were found for the limb going over the hurdle as well as the limb without it. The findings showed that the movement times for both hands were both increasing but were not synchronized. The movement times for the hand going over the barrier were always greater. This limb imposed a bias which resulted in a mimicked increase in movement time in the other, but did not result in perfect temporal or special coordination.

Another spatial-coordination paradigm was studied by Marteniuk, MacKenzie, and Baba (1984). Here the task was to move as quickly and accurately to small point targets. The measured parameter of interest, effective target width, varied when the distance to targets differed. It was observed that when one hand moved to a far target, the other tended to overshoot its closer target and vice versa. The idea that the greater force output required from the limb moving the greater distance affected the smaller force output of the smaller-distance limb was suggested by Sherwood’s 1991 and 1994 studies, (Schmidt 1999).

Alongside of all the research being performed in the second half of the twentieth century on bimanual synergetic topics, many biomechanics and physicists were interested in the dynamical background of human movement. In this time period, growing evidence from bimanual task experiments was suggesting that many interlimb interactions are nonlinear. A combination of variability in organization of control signals and variability in effector mechanisms responsible for producing actions both contributed to inconsistencies in studies of movement.

Some inquisitive researchers realized that gait transitions in four-legged animals could be explained by nonlinear dynamics. Qualitative changes in gait patterns, (i.e. walk, trot, or gallop), are caused by a loss of stability and consequent compensation to achieve maximum stability. By defining a gait as a relative phase, it makes sense that a bifurcation occurs when the control parameter passes through a critical point, resulting in the qualitative change of an attractor, or a gait transition, (Kelso 1999).

To study this concept, Kelso came up with a creative model that allowed subjects to use their fingers to mimic gait transitions. The basic set up of the paradigm was to have subjects oscillate their left and right index fingers back and forth in the transverse plane at the same frequency. Infrared light emitting diodes attached to the fingertips were used to monitor the movement and platinum fine-wire electrodes recorded electro-myographic muscle activity. A pace metronome was used to systematically increase oscillation frequency from 1.25 Hz to 3.50 Hz. Subjects were instructed to adopt the most natural pattern under the conditions, and to keep all rhythmical motions in time with the metronome beat. Under these conditions, humans can perform two basic patterns, in-phase and anti-phase. When in-phase movements are performed, homologous muscle groups of the left and right hands are contracting simultaneously. For anti-phase movements, these muscle groups contract alternately. Results showed that only one of these two stability patterns remains constant beyond a critical point of frequency. When subjects reached oscillations around a certain frequency or critical region, they impulsively switched patterns from anti-phase to in-phase. However, if the subjects began oscillations in the in-phase rhythm, they stay there throughout the whole range of frequencies. Calculating the relative phase of one finger to the other as a point estimate from two time series and calculating the continuous relative phase from phase plane trajectories, provided a mathematical way to observe the transition. These unintended transitions illustrate the natural inclination for specific coordination forms and the concept of self-organization. This idea implies that in order to limit the available degrees of freedom of a system, the brain signals coordination patterns to emerge spontaneously.

Haken, Kelso, and Bunz proposed the HKB model to explain space-time symmetry, bistability, and the observed bifurcation in the "finger-gait" experiments. Their model defines the time and space symmetric function V,

$$V(\varphi) = V(\varphi + 2\pi),$$

$$V(\varphi) = - V(\varphi).$$

By expressing V as a Fourier series, a sinusoidal system,

$$V = - a \cos \varphi - b \cos \varphi,$$

is created, which can exhibit transitions from the symmetrical to anti-symmetrical by changing the ratio of b/a (inversely related to frequency). Taking the derivative with respect to the collective variable, φ, the coordination law is written as,

$$- d V / d \varphi = - a \sin \varphi - 2b \sin 2 \varphi.$$

By examining a vector field diagram, it is noted that as the ratio of b /a decreases, the stable fixed point at $\varphi = \pi$ ultimately vanishes, leaving only the point at $\varphi = 0$. This creates a pitchfork bifurcation, and explains the phenomenon of the transition from anti-phase to in-phase oscillations, (Kelso 1999).

Actions involving synchronization of both upper and lower extremities have been found to share similarities with bimanual coordination tendencies, as well as some original trends. In a study by Baldissera, Cavallari, and Civaschi (1982), subjects synchronized upward and downward ankle movements with specific wrist movements. They found that movements in the same direction to be more stable than those in the opposite direction when the forearm is in the supine position. For example, plantar flexion and wrist extension were closely linked, as were dorsal flexion with wrist flexion. Likewise, when the forearm is in the prone position, movements in the same direction were the most stable, although in this position, they required opposite pairing of muscle groups (i.e. plantar flexion and wrist flexion and dorsal flexion and wrist extension). Through these findings, it appears that when the human brain requires cooperation of numerous body mechanisms, movement direction is given greater precedence than particular muscle groupings, (Schmidt 1999).

The relationship between direction and limb selection was addressed in the work of David Rosenbaum in 1983. He studied relationships of these parameters pertinent in motor control and discovered an intrinsic hierarchy among them, which seems to support the 1982 findings of Baldissera et al. The paradigm he created utilized the concept of pre-cuing, or providing a subject with advanced information on how they will be required to move. A response panel was used which provides subjects with various response options. Upon a stimulus, subjects have the option of moving their left or right arm from “home” keys to targets. Additional dimensions in the response options were direction and extent of movement. Subjects were required to move as fast as possible to colored targets, corresponding with the appearance of colored dots that served as the stimulus. Information or pre-cues about none, one, two, or three of the dimensions of the upcoming movement was given prior to the stimulus. The results showed that reaction time decreased as the number of dimensions given in the pre-cue increased. It was also noted that reaction time was faster if direction was pre-cued and not the limb, that if the arm that was to move was pre-cued, but no direction. This suggests that the brain organizes parameters in a hierarchy, in which direction reigns over particular groupings of muscles, (Magill 1986).

Kelso and Jeka performed a further investigation of multi-limb coordination dynamics in 1992. They set up a model using a multi-articulator coordination device (MAC), an apparatus which allows three combinations of inter-limb pairings (homologous, ipsilateral, and contralateral). Oscillatory movements, consisting of flexion and extension in the same and opposite directions were performed varying these combinations, once again a fashion mimicking quadrupedal gaits. In general, it was observed that limbs were more stable when moving in the same direction, though homologous limb pairs were stable when moving in either direction. It was also observed that contralateral paired limbs had stronger upper-lower limb synchrony than did ipsilateral pairs. These results differ patterns seen in bimanual experiments, providing evidence that movement coordination doesn’t follow the same bimanual patterns when dealing with upper and lower extremities, (Schmidt 1999).

Method

Participants

The subjects used in this study were 5 normal student volunteers, 18 to 21 years of age. All participants had full and normal range of motion of their appendages. All subjects were right-handed and naïve to the intention of the experiment. Prior to participation, they were required to sign a consent form approved by William and Mary's Protection of Human Subjects Committee. A chart of general participant information is provided in Table 1.

Experimental Setup and Equipment

The paradigm presented in this experiment was designed specifically to examine spatial and temporal differences between hand and foot movements under various conditions. Subjects were seated upright at a table so that all four limbs were visible from a front-view camera across the room. On the face of the table, two targets indicated by 1-inch crosshair marks were positioned 45 cm apart (center to center). Identical targets were located directly below on the floor. A 20 cm high barrier was placed halfway between the top or bottom targets depending on the condition being tested.

All four targets, the top center of the barrier, and the subject's middle fingers and second toes were marked with light reflectors. The reflectors were made with light foam balls and covered with illuminating material. They were designed to reflect light directly back to the camera so that marked points of interest could be detected by the data reduction program. The camera used was a Panasonic (PV-DV73) digital video camera.

The shutter was set at 1/250 sec/picture in order to accurately capture the high-speed motions. To decrease error in measurement, the camera was aligned parallel with the floor and perpendicular to the subject movement. A visual image of a subject in position to perform a trial is provided in Figure 1A.

A computer program written with Basic provided a preparatory auditory stimulus to the subject followed by a variable fore-period, and a final "go" signal. The program was connected to a circuit which output 5 volts to a light when each sound frequency was emitted. The light served as a visual indicator to the camera that was used to determine reaction time. The digital camera was set up to record all motions made by the subjects and send this information to the reduction program, "Peak Motus", version 7.2, by Peak Performance Technologies.

Procedure

Once the subject was situated at the apparatus they were given verbal instructions of the discrete tasks they were to perform. The experiment was initiated by an auditory stimulus. The subject attempted to move one hand and one foot simultaneously from start to target location (horizontal translation). One appendage (hand or foot) was required to also move vertically to clear the barrier. The camera recorded the motion of both appendages by tracking the light reflected off the point reflectors. Figure 1B is an illustration of a subject who has just completed performing a trial. The trajectories of the movements are overlaid on the image.

The moving hand, moving foot, direction, and placement of the barrier varied over thirty-two conditions. The thirty-two conditions were organized into two phases.

Phase *a* included all 16 combinations of movements in which limbs move in the same direction, e.g: right hand, right foot, medial direction, hand barrier (RRMH); left hand, right foot, lateral direction, foot barrier (LRLF), and so forth. Phase *b* included the same 16 possible combinations of movements, with the limbs moving in opposite directions. A matrix of the movement combinations are given in Figure 2. The order of the combinations was chosen randomly within phases, as was the order of phases.

The subjects were told to try and move from center to center of the cross-hair targets and to hold their position once they finished each movement. They were reminded to complete the movements as fast as possible, while maintaining a reasonable amount of accuracy. Each subject was allowed a practice session consisting of no more that three tries for the following conditions: moving the hand separately with and without the barrier, moving the foot separately with and without the barrier, and moving the hand and foot together with and without the barrier. The practice sessions were intended to have the subjects become familiar with the movements so they could perform them easily, but not so well that it became a learned task. Once the practice was complete, the subjects executed the 32 conditions three times each with a break in between phases *a* and *b*, for a total of 96 trials. All complete test sessions were recorded with the camera and stored in the computer.

<u>Data Reduction</u>

The recorded video input was sent to the data reduction program, “Peak Motus”. This software program is a Windows-based motion capture program that translates video input into coordinates of moving points. The transcribed data can then be used to analyze the movements.

A spatial model of the paradigm was developed, which specified the points of interest as a ball and stick model, as shown in Figures 2A and 2B. This model was the template for all the trials recorded, since they were all variations of the same movement theme. The coordinates of the points of interest in the experiment, (those marked by reflectors), were detected by a set light threshold; the program recognizes only the points within this threshold of pixel intensity level. A “minimum marker outline” and a “maximum marker outline” were also set to define the minimum and maximum number of adjacent pixels whose sum could be recognized as a marker. This ensured that the program would not accidentally pick up miscellaneous points while digitizing the data. Using a frequency of 60 pictures per second and a sample size of 110, the program automatically digitized the reflector points in each picture, recording their position in pixels. A calibration factor was setup, using a control unit, to transform the pixel locations into real life units (meters). The bottom left corner of the video image was defined as the default coordinate origin.

After the data were taken and digitized, each of the trials to be used for analysis was examined. Inadequate trials, in which the subject did not perform the motions properly, (e.g. anticipated stimulus, moved around the barrier rather than over it, accidentally hit the barrier, etc.), were discarded. The occurrences of particular events of interest were manually identified for each of the usable trials kept. These events included the start and end of movement of the hand and foot motions.

Once all the data was analyzed, the variables pertinent to the analysis were extracted. The dependent variables of interest to this experiment were maximum limb height, maximum velocity, and movement time. "Peak Motus" obtained two-dimension scaled coordinates through the set-up calibration. Two-dimensional linear velocity was calculated given the time series of displacement coordinates, d_i, $i = 1,\ldots n$, where d_i, is displacement at the i-th time. The following algorithm was used, where Δt is the time increment:

for i=1, forward difference:

$$v_i = (-d_{i+2} + 4\, d_{i+1} - 3\, d_i) / 2\Delta t$$

for i=2,…,n-1, second order central difference:

$$v_i = (d_{i+1} - d_{i-1}) / 2\Delta t$$

for i=n, backward difference:

$$v_i = (d_{i-2} - 4\, d_{i-1} + 3\, d_i) / 2\Delta t.$$

Intervals with skipped pictures could be interpolated or "masked" with the existing data. (Peak Performance Technologies, Inc., 2002) Movement time for hands and feet was determined by retrieving and subtracting the times of the indicated start events from the ending events.

Another useful method with which data were examined and extracted was through the program's trajectory and plotting functions. The data for each trial could be mapped as a trajectory in space, as well as plotted onto XY graphs. These functions were useful for gathering an overall interpretation of the collected motions and for noticing any trends or discrepancies in the data.

Analysis

The dependent variables chosen for analysis were maximum limb (hand or foot) displacement, maximum limb velocity, and movement time. The data were examined and shown to be from a normal distribution. These variables were then tested for significance using a one tail t-test for displacement, and a two tail t-test for velocity and movement time. The statistics program S-PLUS 6.1 was used to perform the statistical calculations.

Results

Analysis of the data was performed by a conducting one tail t-test, ($P > 0.5$), on the values obtained for maximum limb height. For trials with the hand barrier, the difference between the maximum hand displacement, HB_{hx}, and the maximum foot displacement, HB_{fx} was computed; a small difference between these numbers implies that the foot is mimicking the hand motion. The difference between the maximum foot displacement, FB_{fx}, and the maximum hand displacement, FB_{hx}, was computed for foot barrier trials; in this case, small differences mean the hand is imitating the motion of the foot.

These data differences where then sorted into pairs of correlating trials, (e.g. RRMH and RRMF, RRLH and RRLF, etc.). The random variable X_i was defined as,

$$X_i = (HB_{hx} - HB_{fx}) - (FB_{fx} - FB_{hx}),$$

where i = 1…n trials. The values obtained for X were organized into a data matrix, shown in Table 3. Since the experimental hypothesis assumed that the vertical distances cleared by the hand when moving in synchrony with the foot clearing the barrier are greater than that of the foot when the hand is clear the barrier, the theory was to prove that $X > 0$. The null hypothesis H_0: $\mu \leq 0$ versus, H_1: $\mu > 0$ was tested for each of the 16 trials, using a one-sided, one-sample t test. The test statistic value was found using the equation,

$$t = (\text{mean } x - \mu) / (\text{sqrt}(s) / \text{sqrt}(n)),$$

where x is the mean of the ΣXi ($i = 1 \ldots n$ trials), μ is the test value, s is the sample variance, and n is the sample size. S-PLUS 6.1 was used to evaluate the significance probabilities, which can be found in Table 4. All, except two of the sixteen significance probabilities were remarkably small ($p < .05$). Thus the null hypotheses were rejected and the theory confirmed.

It is easy to visualize this result by studying Figures 3 and 4, sample displacement plots from a subject's performance of a hand barrier and a foot barrier trial, respectively. Just from examining the plots for these two trials, this major result can be seen by noticing that in Figure 3A, (a hand-barrier trial), the vertical displacement of the foot is quite small. Contrastingly, in Figure 3B, (a foot-barrier trial), the vertical displacement of the hand is visibly greater.

The data were further analyzed through an examination of trends in the mean values of maximum velocity and movement time. These values, along with a measure of standard deviations, are shown in Tables 5 and 6. Figures 5A and 5B show this data charted. It appeared through comparison that a general trend was for the hand to have a greater initial velocity than the foot and to almost always begin moving first, as seen in Figures 4A and 4B. This phenomenon can be partially explained as follows: In the case where the hand must clear the barrier, it travels faster and farther than the foot because the foot mimics the hand's obstacle clearing motion very poorly; i.e. its vertical motion is much smaller than that of the hand and it moves more slowly. In the case where the foot must clear the obstacle, we find that the hand is a better mimic and consequently travels vertically a large amount. To finish in time, it anticipates it will have to speed up and appears to over-compensate initially when it does so.

Discussion

The results of the data analysis are consistent with the hypothesis that, in the performance of synchronized movements, the foot effects hand more than the hand effects the foot. The data also show that the velocity and movement time of the hand appears to be greater than the velocity and movement time of the foot.

It could be concluded from our data that when the brain is faced with the task of controlling multiple degrees of freedom, it adopts an optimal solution by automating the motion of the hand. The brain seems to instinctively control the hands action, leaving it susceptible to be influenced by the task being performed by the foot; a motion which requires more cognitive attention. An interesting and unexpected trend observed from our data that supports this idea, was that for a vast majority of the trials, the subjects initiated hand movements before foot movements. This idea could be tested through tests with a variation of our model, in which subjects are required to perform a similar set of trials, while intentionally focusing on the movement of the hand or the foot.

This experimental paradigm has potential has potential for further examination of interlimb coordination. For example, other dependent variables, such as time to maximum velocity and time to maximum acceleration could be examined to see if significant differences in values exist for hands and feet. Another idea is to reverse the subject's visual feedback by having them look at targets on a screen, correlated to the hand and foot targets, but in the reverse order (i.e. foot on top, hand on bottom). An examination of maximum limb displacement could be used to determine whether a limb has a spatial advantage by being visibly closer.

The theory behind this experiment could be further substantiated with more data from a larger group of subjects. The results are significant enough to provoke the initiation of a larger test.

References

Kelso, J.A.Scott. (1999). Dynamic Patterns: The Self-Organization of Brain and Behavior. Cambridge, Massachusetts: The MIT Press.

Kelso, J.A.S, Jeka, J.J., (1992). Symmetry breaking dynamics of human multilimb coordination. Journal of Experimental Psychology: Human Perception and Performance, 18, 645-668.

Kelso, J.A.S., Southard, D.L., & Goodman, D. (1979). On the Coordination of tow-handed movements. Journal of American Psychology: Human Perception and Performance, 5, 229–238.

Magill, Richard A. (1989) Motor Learning: Concepts and Applications, 3rd Edition. Dubuque, Iowa: Wm. C. Brown Publishers.

Newell, K.M., Corcos, D.M. (1993). Variability and Motor Control. Champaign, IL: Human Kinetics Publishers.

Peak Motus. (2002). Peak Motus Version 7.2, User Manuel. Englewood, CO: Peak Motus Technologies, Inc.

Rosenbaum, David A. (1991). Human Motor Control. San Diego, CA: Academic Press, Inc.

Schmidt, Richard A., Lee, Timothy D. (1999). Motor Control and Learning. Champaign, IL: Human Kinetics Publishers.

Swinnen, S., Heuer, H., Massion, J., Casaer, P. (1994). Interlimb Coordination: Neural, Dynamical and Cognitive Constraints. Academic Press, Inc.

Table 1

<u>Subject Information</u>
Information provided by participants.

Subject #	Age (yrs)	Height (ft)	Weight (lbs)	Dominant Hand
72	19	5’ 7”	129	Right
73	20	5’ 4”	130	Right
74	22	5’ 4”	135	Right
75	22	5’ 5”	130	Right
76	21	5’ 6”	130	Right

Table 2

Matrix of movement combinations

All possible movement combinations which subjects were required to perform. Phase a included all movements in which limbs moved the same direction. Phase b repeated these movements, with limbs moving in the opposite direction.

Condition	Moving Hand	Moving Foot	Direction	Barrier
1	Right	Right	Medial	Hand
2	Right	Right	Medial	Foot
3	Right	Right	Lateral	Hand
4	Right	Right	Lateral	Foot
5	Left	Left	Medial	Hand
6	Left	Left	Medial	Foot
7	Left	Left	Lateral	Hand
8	Left	Left	Lateral	Foot
9	Right	Left	Medial	Hand
10	Right	Left	Medial	Foot
11	Right	Left	Lateral	Hand
12	Right	Left	Lateral	Foot
13	Left	Right	Medial	Hand
14	Left	Right	Medial	Foot
15	Left	Right	Lateral	Hand
16	Left	Right	Lateral	Foot

Table 3

Matrix of X_i values

1(1a-2a)	.096	.131	.065	.128
2(1b-2b)	.174	.126	.195	.121
3(3a-4a)	.110	.223	.218	NA
4(3b-4b)	.176	.136	.221	.100
5(5a-6a)	.156	.072	.205	-.013
6(5b-6b)	.167	.164	.315	.099
7(7a-8a)	NA	.321	.111	.151
8(7b-8b)	.194	.224	.176	.097
9(9a-10a)	.193	.160	.277	.034
10(9b-10b)	NA	.201	.150	.103
11(11a-12a)	.092	.103	.083	.045
12(11b-12b)	.088	.150	.205	.087
13(13a-14a)	.130	.245	.176	.190
14(13b-14b)	.089	.171	.081	.087
15(15a-16a)	.001	.205	.178	.043
16(15b16b)	.197	.257	.183	NA

Table 4

<u>Summary of t-test statistics</u>
All test used with $p > 0.5$

Trial	H_0	p	Result
1	$\mu_0 \leq 0$	0.00329	Reject H_0
2	$\mu_0 \leq 0$	0.00171	Reject H_0
3	$\mu_0 \leq 0$	0.01900	Reject H_0
4	$\mu_0 \leq 0$	0.00448	Reject H_0
5	$\mu_0 \leq 0$	0.05819	Decline to Reject H_0
6	$\mu_0 \leq 0$	0.01333	Reject H_0
7	$\mu_0 \leq 0$	0.04723	Reject H_0
8	$\mu_0 \leq 0$	0.00392	Reject H_0
9	$\mu_0 \leq 0$	0.02300	Reject H_0
10	$\mu_0 \leq 0$	0.01662	Reject H_0
11	$\mu_0 \leq 0$	0.00385	Reject H_0
12	$\mu_0 \leq 0$	0.00921	Reject H_0
13	$\mu_0 \leq 0$	0.00218	Reject H_0
14	$\mu_0 \leq 0$	0.00770	Reject H_0
15	$\mu_0 \leq 0$	0.06117	Decline to Reject H_0
16	$\mu_0 \leq 0$	0.00561	Reject H_0

Table 5

Maximum Velocity Values Summary

This table shows the mean value of the maximum velocity values in the data, along with a measure of the standard deviation of these values. The data is grouped by trials depending upon barrier position, limb, and direction of movement.

	Hand Barrier: Hand-Same	Hand Barrier: Hand-Opposite	Hand Barrier: Foot-Same	Hand Barrier: Foot-Opposite	Foot Barrier: Hand-Same	Foot Barrier: Hand-Opposite	Foot Barrier: Foot-Same	Foot Barrier: Foot-Opposite
Mean v_{max} (m/s)	3.924	3.670	3.117	2.875	2.876	2.682	2.960	2.720
Σstd dev	0.4230	0.401	0.448	0.538	0.547	0.637	0.546	0.654

Table 6

Movement Time Values Summary

This table shows the mean value of the movement times for each trial, grouped according to barrier position, limb, and direction of movement.

	Hand Barrier: Hand-Same	Hand Barrier: Hand-Opposite	Hand Barrier: Foot-Same	Hand Barrier: Foot-Opposite	Foot Barrier: Hand-Same	Foot Barrier: Hand-Opposite	Foot Barrier: Foot-Same	Foot Barrier: Foot-Opposite
Mean Mt (s)	0.349	0.358	0.248	0.256	0.328	0.336	0.360	0.370
Σstd dev	0.040	0.047	0.036	0.046	0.069	0.069	0.070	0.060

Figure Captions

Figure 1A. Image of a subject in position to perform a trial.

Figure 1B. Image of a subject who has completed a trial. Overlying trajectories mark the path of motion.

Figure 2A. Spatial model that was used as a template for all the trials. Marked points are: Moving hand, moving foot, hand targets, foot targets, and foot barrier positions.

Figure 2B. Spatial model with hand barrier.

Figure 3A. Displacement versus time graph for a hand-barrier trial.

Figure 3B. Displacement versus time graph for a foot-barrier trial.

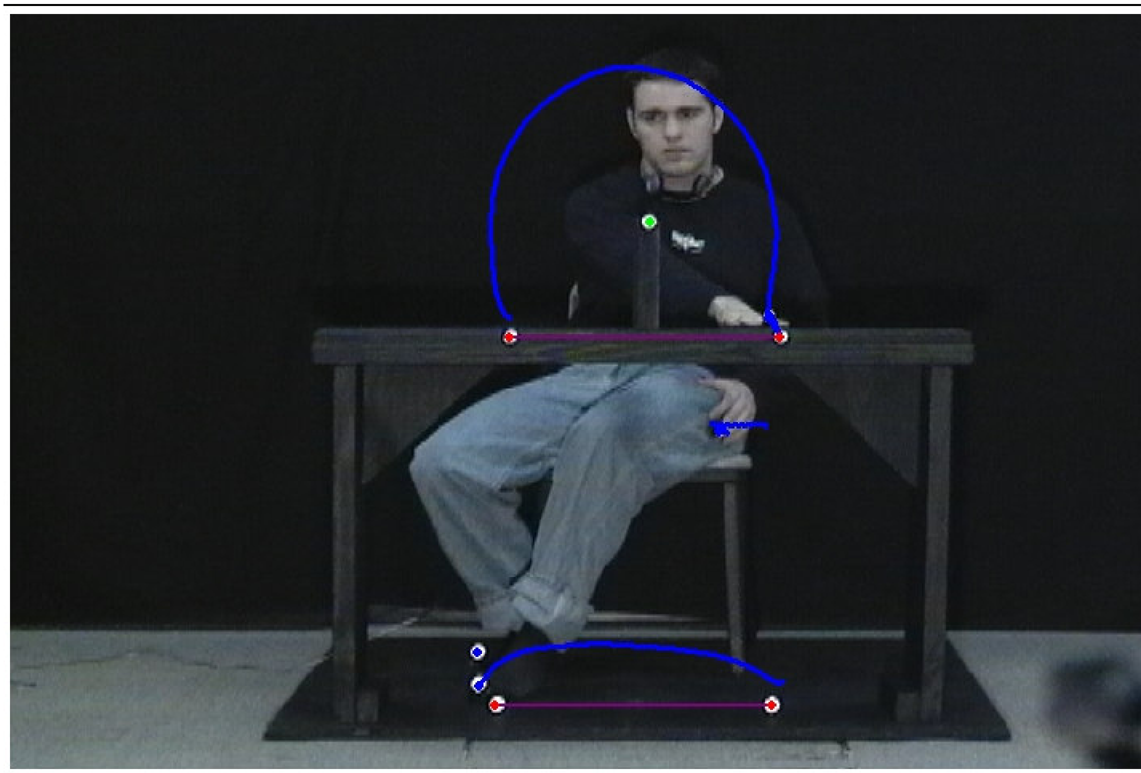
Figure 4A. Velocity versus time for a hand-barrier trial.

Figure 4B. Velocity versus time for a foot-barrier trial.

Figure 5A. Mean maximum velocity as a function of barrier position, limb, and direction of movement.

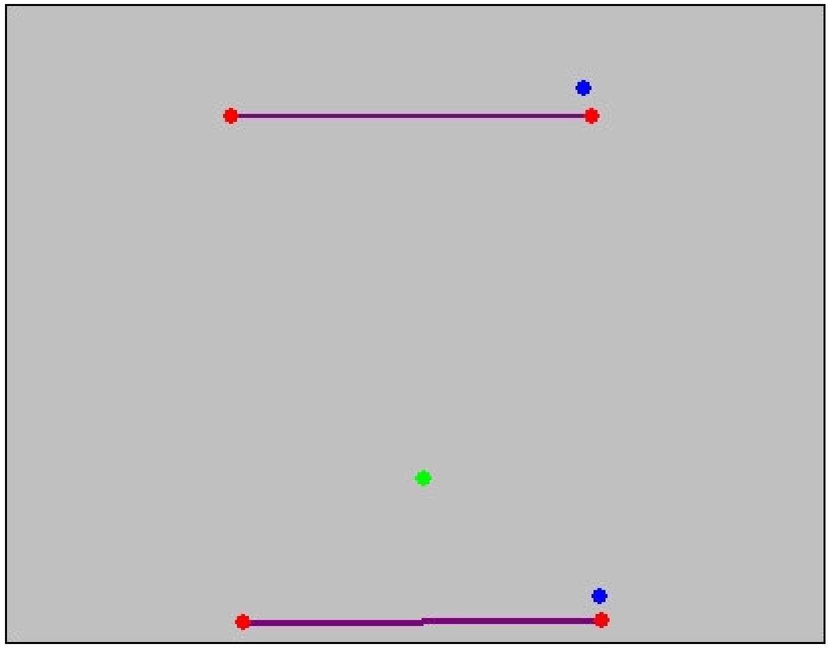
Figure 5B. Mean movement time as a function of barrier position, limb, and direction of movement

A.

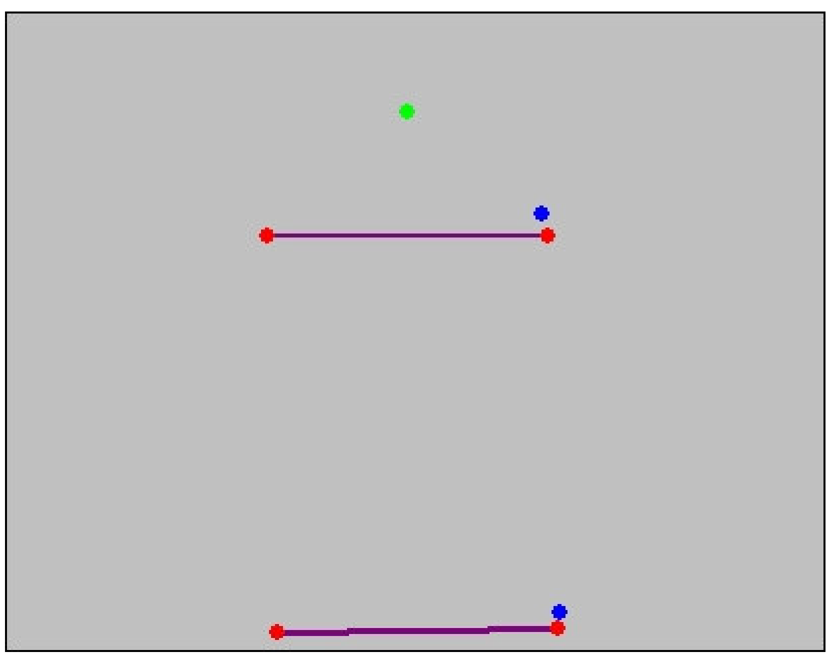


B.

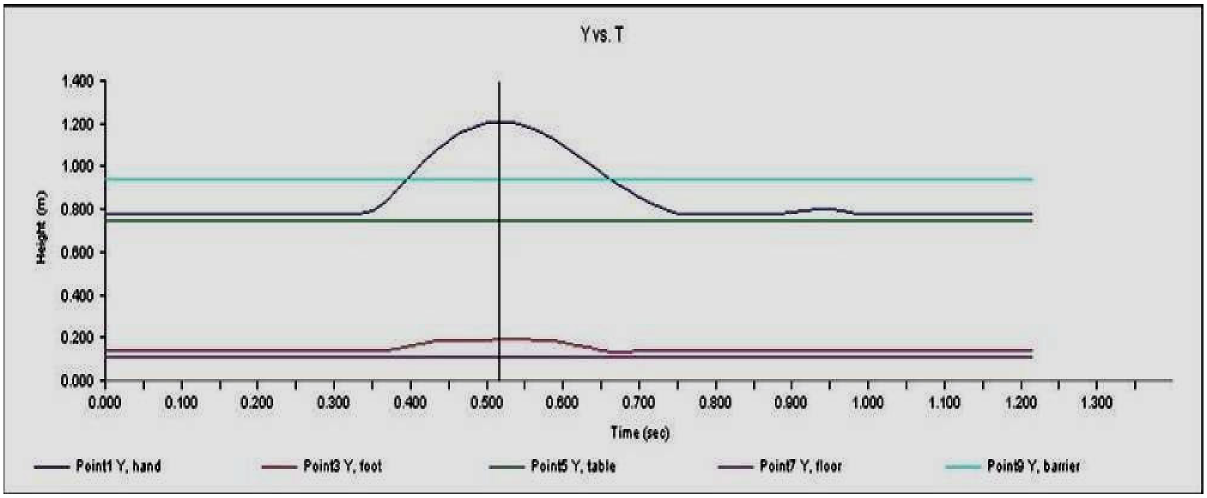
A.



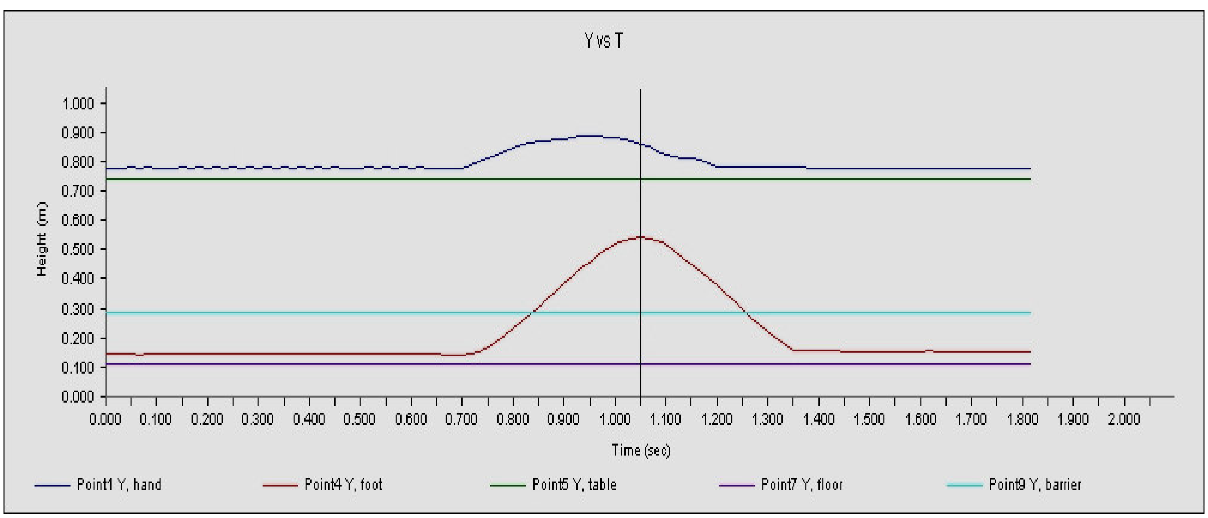
B.



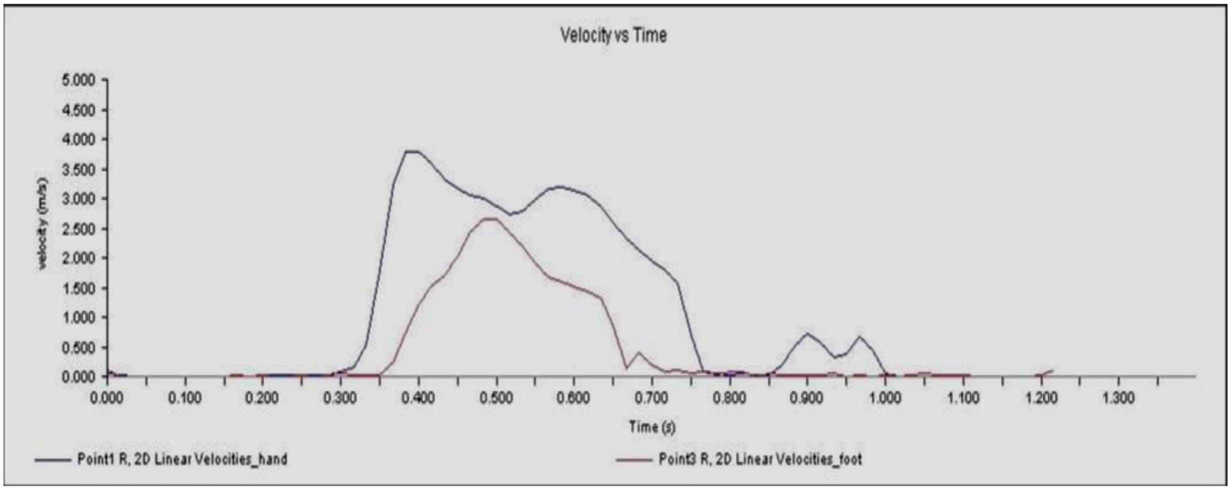
A.


Y vs. T
Height (m)
1.400
1.200
1.000
0.800
0.600
0.400
0.200
0.000
0.000 0.100 0.200 0.300 0.400 0.500 0.600 0.700 0.800 0.900 1.000 1.100 1.200 1.300
Time (sec)
Point1 Y, hand
Point3 Y, foot
Point5 Y, table
Point7 Y, floor
Point9 Y, barrier

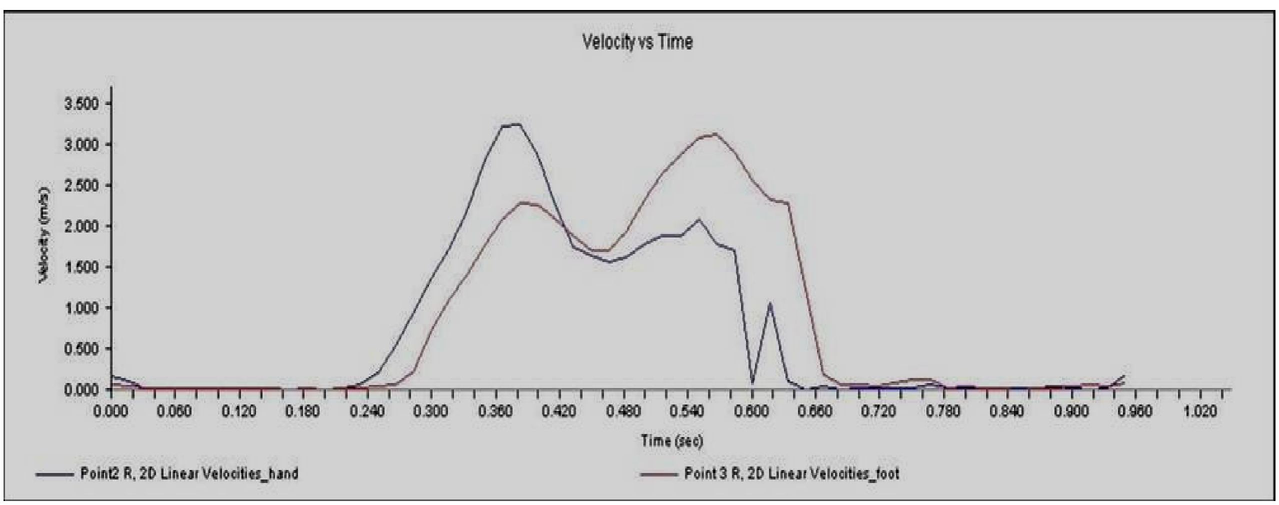
B.


Y vs T
Height (m)
1.000
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0.000 0.100 0.200 0.300 0.400 0.500 0.600 0.700 0.800 0.900 1.000 1.100 1.200 1.300 1.400 1.500 1.600 1.700 1.800 1.900 2.000
Time (sec)
Point1 Y, hand
Point4 Y, foot
Point5 Y, table
Point7 Y, floor
Point9 Y, barrier

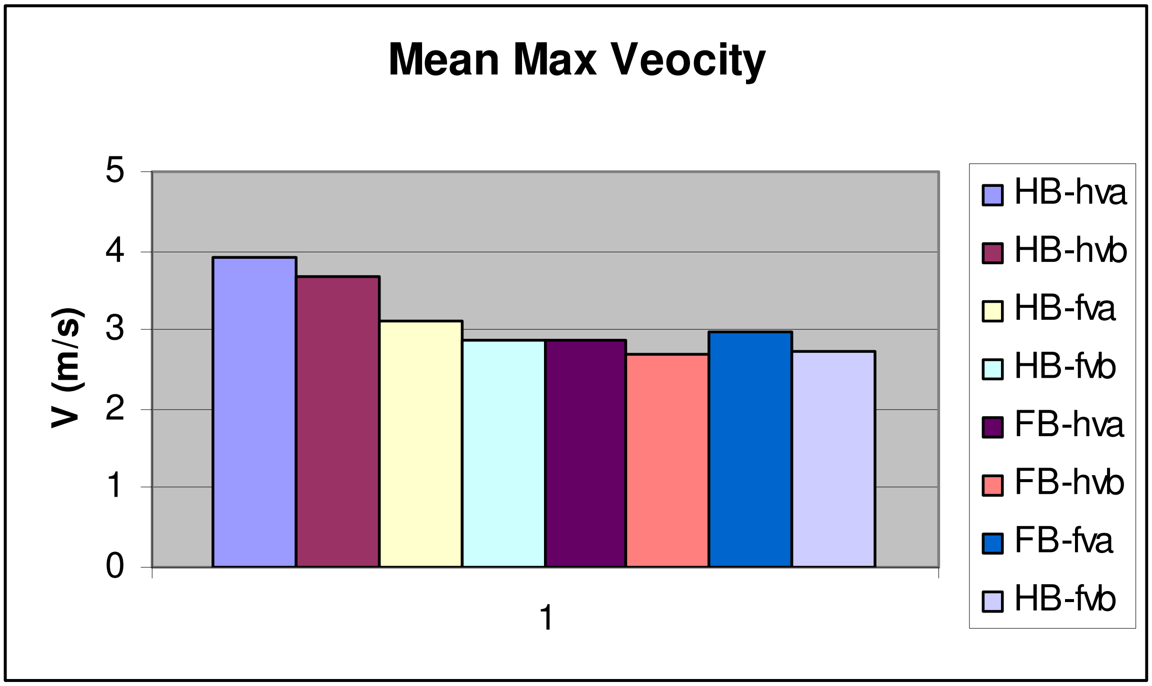
A.


Velocity vs Time
velocity (m/s)
5.000
4.500
4.000
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
0.000
0.100
0.200
0.300
0.400
0.500
0.600
0.700
0.800
0.900
1.000
1.100
1.200
1.300
Time (s)
Point1 R, 2D Linear Velocities_hand
Point3 R, 2D Linear Velocities_foot

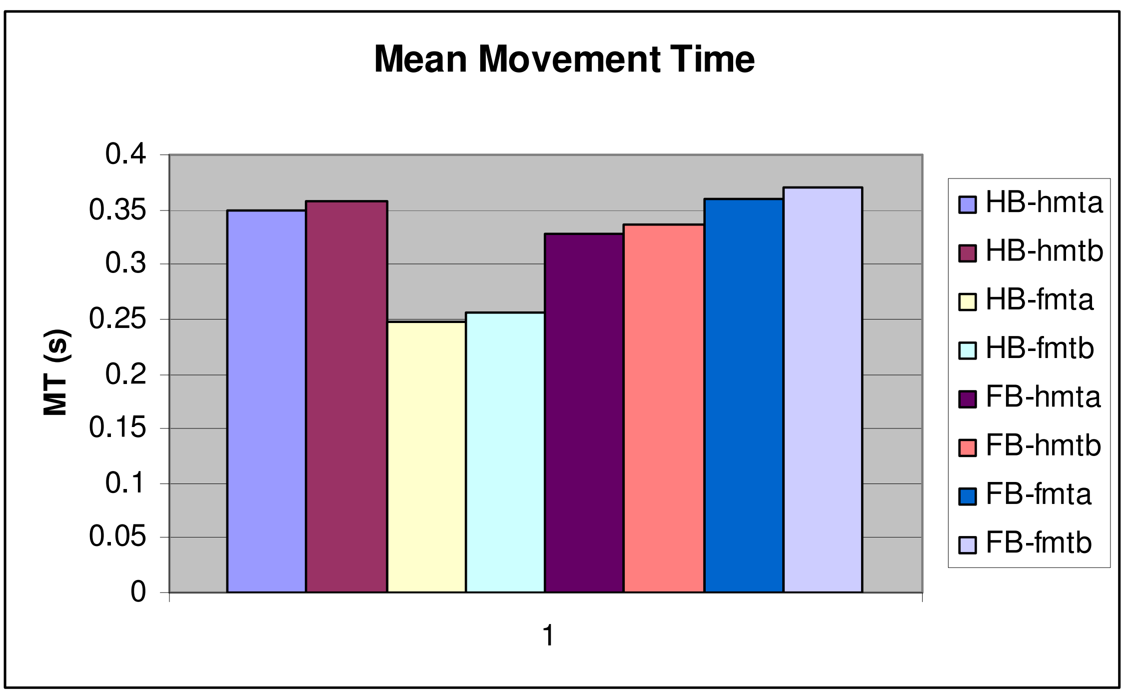
B.


Velocity vs Time
Velocity (m/s)
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
0.000
0.060
0.120
0.180
0.240
0.300
0.360
0.420
0.480
0.540
0.600
0.660
0.720
0.780
0.840
0.900
0.960
1.020
Time (sec)
Point2 R, 2D Linear Velocities_hand
Point 3 R, 2D Linear Velocities_foot

A.


Mean Max Veocity
V (m/s)
5
4
3
2
1
0
1
HB-hva
HB-hvb
HB-fva
HB-fvb
FB-hva
FB-hvb
FB-fva
HB-fvb

B.


Mean Movement Time
MT (s)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1
HB-hmta
HB-hmtb
HB-fmta
HB-fmtb
FB-hmta
FB-hmtb
FB-fmta
FB-fmtb