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Motor performance of tongue with a computer-integrated system under different levels of background physical exertion

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Abstract

The purpose of this study was to compare the motor performance of tongue, using Tongue Drive System, to hand operation for relatively complex tasks under different levels of background physical exertion. Thirteen young able-bodied adults performed tasks that tested the accuracy and variability in tracking a sinusoidal waveform, and the performance in playing two video games that require accurate and rapid movements with cognitive processing using tongue and hand under two levels of background physical exertion. Results show additional background physical activity did not influence rapid and accurate displacement motor performance, but compromised the slow waveform tracking and shooting performances in both hand and tongue. Slow waveform tracking performance by the tongue was compromised with an additional motor or cognitive task, but with an additional motor task only for the hand.

Practitioner Summary—We investigated the influence of task complexity and background physical exertion on the motor performance of tongue and hand. Results indicate the task performance degrades with an additional concurrent task or physical exertion due to the limited attentional resources available for handling both the motor task and background exertion.

Keywords

assistive device; dual task; finger; motor control; tongue

Introduction

It is evident from the motor homunculus (functional cross-section of the human motor cortex) that the tongue and mouth occupy an amount of motor cortex in the human brain that rivals that of the fingers and the hand (Kandel et al. 1991). Hence, they are inherently

capable of sophisticated motor control and manipulation tasks, with many degrees of freedom, that are often utilised in speech and ingestion. Until recently, there were no feasible methods to harness the rich natural motor capabilities of the tongue and the numerous degrees of freedom that it can offer as a human motor output in daily tasks that involve manipulation and actuation. This limitation has now been circumvented to a high extent by the invention of a new wireless and wearable technology, known as the Tongue Drive System (TDS), that can translate the voluntary tongue motion to a set of user-defined commands in real time (Ghovanloo 2007; Huo, Wang, and Ghovanloo 2007a).

The TDS consists of a small permanent magnetic tracer, an array of 3D magnetic sensors and a processing unit. The magnetic tracer is the size of a lentil and is attached to the tongue via adhesives (temporarily) or piercing (semipermanently), the magnetic sensors are positioned near the cheeks on a headset, and the processing unit can be a wearable computer, such as a smartphone. Moving the tongue changes the magnetic field distribution inside and around the mouth. The sensor array picks up the changes in the magnetic field distribution and wirelessly sends them to the smartphone via the electronics embedded in the headset. A sensor signal processing (SSP) algorithm running on the smartphone processes this information to detect the user-defined command, and deliver it to the target device or home appliance, such as a PC or TV via Bluetooth or wireless local area network.

Utilising the tongue motion as a means to control the environment can offer considerable benefits to individuals with high level disabilities, such as quadriplegia, because the tongue is directly connected to the brain via the hypoglossal nerve. Therefore, even the highest level spinal cord injury does not affect the tongue motion. Unlike most skeletal muscles, the tongue muscle has a very low rate of perceived exertion and can be used over extended periods. Additionally, the position of the tongue may be controlled independent of the position of the limbs and torso. Therefore, TDS can be used while sitting on a chair or lying in bed. These advantages and the accessibility of the tongue point out to the fact that tongue can potentially be employed as an excellent intermediate connection to the brain for various motor control and manipulation tasks (Huo and Ghovanloo 2010).

TDS can also be used by able-bodied individuals that are engaged in military, civilian or entertainment activities that have a high level of control demand, such as pilots and gamers. It can also be used in environments that limit the physical motion of the upper extremities, such as in heavy suites for space and deep underwater operations. In these conditions, operators need to engage their fingers and the tongue either sequentially or simultaneously to accomplish the designated tasks and at the same time deal with other types of background physical or mental exertion such as walking, thinking and decision-making.

There is a large body of literature on the neurophysiology and function of hand muscles. More specifically, the index finger is the most frequently used finger in the hand in everyday life, and the muscle that abducts and flexes the index finger (first dorsal interosseus muscle, the muscle that moves the index finger towards the thumb and the palm) is the subject of most muscle studies in the human hand (Enoka et al. 2003; Shinohara, Keenan, and Enoka 2003). Researchers have also studied the simultaneous use of both hands in presence or

absence of background physical exertion (Hiraga et al. 2009; Johnson, Wheaton, and Shinohara 2011; Kaluzny, Palmeri, and Wiesendanger 1994).

However, very little is known when the tongue is engaged as a human motor output either by itself or in addition to hand functions. In our previous report (Johnson et al. 2012), we have examined the characteristics of tongue motor performance in simple motor tasks, i.e. rapid discrete movement, rapid continuous movement and waveform tracking while sitting quietly. It was found that rapid goal-directed hand and tongue movements were consistently susceptible to interference from concurrent motor and cognitive tasks. The characteristics of tongue motor performance during more complex tasks under whole body physical exertion are unknown. The purpose of the study was to compare the motor performance of tongue, using TDS, to hand operation for relatively complex tasks under different levels of background physical exertion.

Methods

Experimental design

Subjects performed experimental trials in three sessions. In each session, subjects controlled the movement of a computer cursor (or cursors) that corresponded to the movement of their tongue or right index finger. The sessions were conducted in a random sequence on three days that were separated by more than seven days for each subject. Results in sessions 1 and 2 that tested motor performance in simple tasks with the tongue and index finger have been reported elsewhere (Johnson et al. 2012). The current paper reports session 3 that tested the tongue and hand motor performance in completing relatively complex tasks under different levels of background physical exertion.

Subjects

Thirteen healthy, young, right-hand-dominant adults (age: 20–26 years old; seven men and six women) participated in the study. None of them had any history of neurological disorder. Subjects refrained from caffeine and nicotine at least 2 h prior to the experiment. Handedness of the subjects was confirmed with the Edinburgh Handedness Inventory (Oldfield 1971). Subject's written consent was obtained in accordance with the Institutional Review Board of Georgia Institute of Technology and the US Army Research Office.

TDS set-up

In all experiments, subjects wore a TDS headset (Figure 1A), and TDS set-up was performed before experiments. The magnetic sensors of the TDS, which were mounted on a pair of goosenecks, were positioned close to the subjects' cheeks so the sensors detect variations of the magnetic field resulting from the movement of the magnetic tracer in the mouth with a high signal-to-noise ratio. Subjects walked around the test set-up to let the SSP algorithm identify the background magnetic noise (primarily from the earth's magnetic field) which needed to be cancelled out during the experiments. Then a small (5 mm diameter, 1.5 mm thick) nickel plated rare-earth permanent magnet (K&J Magnetics, Jamison, PA) with 13,500 Gauss residual flux density was attached near the tip of the subjects' tongue using Cyanodent dental adhesive (Ellman International, Oceanside, NY)

(Figure 1B). The position of the magnet on the subjects' tongue was noted by marking to ensure that they could be re-attached in the same positions if detached.

The TDS prototype can detect up to six user-defined 'tongue commands', which have been originally assigned to cardinal cursor movements and single/double clicks to substitute computer mouse functions (Huo, Wang, and Ghovanloo 2008). In this study, we only used four directional commands to move the mouse cursor, while disabling the click functions. Before using these commands, subjects were required to define them for the SSP algorithm in a calibration session (Huo, Wang, and Ghovanloo 2007b). This was accomplished by identifying specific positions for the tip of the tongue in their mouth and associating these positions to different 'tongue commands'. For instance, subjects may touch the lower left canine teeth with the tip of their tongue and define it as the LEFT command. During the calibration session, subjects were instructed to consistently place their tongue at four recommended positions that were assigned to LEFT, RIGHT, UP and DOWN commands in a sequence, 10 times in a row, such that TDS would collect enough magnetic sensor data for those specific commands and extract the principal features for those commands based on the recorded data. Later on, when subjects placed their tongue at those specific positions, TDS correctly associated those positions to the tongue commands.

Experimental protocol

The study tested the accuracy and variability in tracking a sinusoidal waveform, and the performance in playing two video games that require accurate and rapid movements with cognitive processing using tongue and hand under two levels of background physical exertion. The experiment was divided into three parts: slow tracking of a waveform (Part 1), playing a game that required rapid and accurate displacement and timing control in a 2D space (Part 2) and playing a game that required rapid and accurate command initiation for shooting while interacting with the accurate displacement control by the left hand (Part 3). During the experiment, subjects wore the TDS headset to perform tongue tasks, while using a force measurement unit (for Part 1) or a game console (for Parts 2 and 3) by their hands to perform hand tasks (Figure 2). A monitor (15 inch, 1280 × 800 resolution) was fixed on the treadmill and placed ~ 0.5 m in front of the subjects to provide visual feedback.

There were two different conditions for background physical exertion by employing a walking on a treadmill (Gold's Gym 450, Gold's Gym International, Irving, TX) through the duration of the trial. In the low exertion condition, subjects walked slowly (0.45 m/s) on a flat surface. In the high exertion condition, subjects walked briskly (1.79 m/s) on an inclined (4%) surface. These two conditions were used so that subjects have contrasting levels of physical exertion. The study did not include any tests without background physical exertion. Treadmill walking was chosen because it is the most accustomed form of whole body exercise without requiring much attention for most people. The order of the tasks and background physical exertion were randomised. In addition to the hand and tongue performance measures, heart rate, rating of perceived exertion (RPE, 0–10 scale) for background physical exertion and rating of perceived difficulty (RPD, 0–10 scale) in performing the task were also measured for each task using a standard scaling method for

assessing psychophysical exertion (Borg 1982). Heart rate was measured using a sports chest band (ORMON HR-100C, Warminster, PA).

Part 1: slow waveform tracking

Subjects used their tongue and/or index finger to control the vertical position of a marker moving up and down to track a sinusoidal waveform (Figure 3A). Each trial lasted 20 s. The waveform consisted of one cycle of sinusoidal waveform with a period of 15 s after a 5-s period at the resting level. A sinusoidal waveform was used for assessing the capability of tongue and hand for accurately controlling their motor output continuously to match rhythmically and smoothly changing targets. The sinusoidal waveform was the same as the one that was used in our previous study on the tongue and hand (Johnson et al. 2012). There were five tasks: independent hand (H), independent tongue (T), concurrent hand and tongue (HT), concurrent hand and cognitive (HC), and concurrent tongue and cognitive (TC) tasks. Three trials were performed for each task under two different conditions for background physical exertion. Subjects practised each hand/tongue task up to two times before the actual trials.

Hand task—Subjects held a handle of ‘pistol-type’ hand-held force measurement equipment with their right hand, while their index finger pulp pressed on a force transducer in an orientation similar to shooting a gun (Figure 2, inset). This force measurement equipment was used to quantify the accuracy and variability of motor output in a relatively simple setting with a single finger (index). Subjects adjusted the flexion force of the index finger to move the marker on the monitor upward and downward. To impose a similar amount of neuromuscular effort in performing the hand task, the range of finger force production was defined relative to the finger strength in each subject. For this purpose, prior to the experiment, the maximal voluntary contraction (MVC) force of index finger flexion was determined by having subjects press the force transducer with their maximal effort. The target sinusoidal waveform was set to be centred at 20% MVC with an amplitude of 5% MVC.

Tongue task—Sensor outputs from TDS were recorded after noise cancellation and used to represent the position of the tongue. To determine the maximum and minimum sensor outputs, the magnitude of the magnetic field vector was recorded while subjects moved their tongue to extreme positions on the left and right, i.e. touching the edges of their lips, near the left and right cheeks. Subjects were asked to adjust the position of their tongue with visual feedback, i.e. moving them closer to or further away from the left sensor module. The leftward and rightward movement of the tongue controlled the upward and downward movement of the computer cursor, respectively, to be consistent with the hand task (Figure 3A). The amplitude of the target waveform was set to 50% of the maximum change in the sensors’ output when tongue reached the edge of the lips on left.

Cognitive task—Cognitive task required subjects to perform a cumulative math calculation. Subjects were given five math operations verbally during the 20-s trial period. The math operations included single-digit summation, subtraction and multiplication not exceeding 100. The math problems were randomly generated and recorded in computer

audio files, which were replayed in a randomised sequence during the experiment. Subjects were asked only one math problem at a time and memorised the result of the previous calculation that was carried over to the next operation. Subjects reported only the final and accumulated answer immediately, typically within 5 s, after the 20-s trial ended.

Data analysis—The recorded sinusoidal waveforms from each subject were normalised and shifted in time such that waveforms from all subjects had the same starting point and peak-to-peak amplitude. The performance metric of accuracy was defined as the average of the absolute difference between target and real waveforms across one trial (absolute error). In addition, the root mean square (RMS) error was calculated as a measure of variability in displacement. Correctness for the cognitive problems was also assessed in percentage.

Part 2: rapid and accurate displacement and timing control in a 2D space

Subjects played a video game ('Fish Tales', justfreegames.com) that required a rapid and accurate displacement and timing control of a computer cursor in a 2D space to catch or avoid moving objects. They moved the cursor either by hand using a PlayStation™ gamepad (Logitech, Fremont, CA) or by tongue using the TDS (Figure 3B). Subjects controlled the movement of a red fish cursor to catch as many smaller fish as possible while avoiding being caught by larger fish, which would have cost them a life each time. The cursor was moved in an unlatched manner, e.g. the cursor speed ramped up from zero to a pre-defined max value when subjects continuously issued a command using either the finger or tongue. The cursor stopped moving as soon as subjects released their finger or returned their tongue back to the resting position. Subjects were given six lives for the red fish, and the game was terminated when a certain score (430) was reached, lives were used up or after 60 s. Subjects performed individual hand and tongue tasks under the two conditions for background physical exertion.

Hand task—Subjects used their right index finger to press keys '1', '2', '3' and '4' on the PlayStation™ gamepad to move the red fish to left, down, right and up, respectively (Figure 3B).

Tongue task—Subjects touched the lower left, upper right, lower right and upper left teeth (Figure 3B) with the tip of the tongue that corresponded to pressing keys '1', '2', '3' and '4', respectively, on the PlayStation™ gamepad to move the red fish to left, down, right and up, respectively.

Data analysis—A single figure of merit was calculated from the game score, number of lives used and completion time as scoring efficiency = score/(time × live).

Part 3: rapid and accurate command initiation while interacting with the left hand

In Part 2, rapid and accurate motor performance between tongue and hand was compared in a single motor task, i.e. without interacting with another attention-demanding motor task. Part 3 was conducted to understand the effect of background physical exertion on motor performance when interacting with another attention-requiring motor command by the left hand in a multi-motor task. Subjects played a video game that required a rapid and accurate

displacement and timing control of a cross-hair computer cursor in a 2D space to aim at and shoot a randomly appearing target on the monitor. Subjects held the PlayStation™ gamepad with both hands. A target with one of the randomised diameters (radii = 10, 15, 20, 25, 30 pixels) appeared on the screen at an arbitrary position in a 2D space (1000 × 1000 pixels). Subjects controlled the cursor displacement with their left hand and the timing of shooting command initiation with the right hand or tongue (Figure 3C). Each trial included 15 targets and shots, and subjects were asked to shoot as accurately and quickly as possible. The shooting accuracy and timing were measured for hand and tongue in two conditions for background physical exertion.

Hand task—Subjects aimed at the target by moving the cursor using the left joystick of the PlayStation™ gamepad with their left thumb, and shot by pressing the front button on the right with the right index finger (Figure 3C).

Tongue task—Subjects trained the TDS with a *SHOOT* command by simply sticking the tongue out. During the task, subjects aimed at the target by moving the cursor using the left joystick of the PlayStation™ gamepad with their left thumb (same as what they did in the hand task), and shot by sticking the tongue out (Figure 3C).

Data analysis—Shooting error was measured as the distance between actual shooting point and the centre of the real target in pixels. Shooting delay was defined as the time it took for the subjects to correctly trigger a shooting action from the time that the target appeared on the monitor.

Statistical analysis—Measured variables in each part were averaged across three trials in each task. Dependent variables included those of performance merits (absolute error, RMS error, cognitive correctness, scoring efficiency, shooting error and shooting delay) and parameters for exertion (heart rate, RPE and RPD). These variables were tested with a two-way analysis of variance with repeated measures with the factors being task and background physical exertion. Post hoc analyses were performed with a Bonferroni test when appropriate. An alpha level of 0.05 was used for all statistical comparisons, and $p < 0.05$ or $p < 0.01$ was indicated when significance was found. Unless stated otherwise, the data are presented as mean $\pm$ SD in the text and table and mean $\pm$ SE in figures.

Results

In Part 1, heart rate, RPE and RPD were significantly higher during the high versus low background exertion across tasks (Table 1). While there was no significant effect of task on RPE, the heart rate and RPD were influenced by task. Heart rate was significantly higher with an additional cognitive than motor task for both hand (122.2 ± 29.9 in HC vs. 115.9 ± 26.0 beats/min in H, $p < 0.05$) and tongue (122.0 ± 28.0 in TC vs. 115.9 ± 26.0 beats/min in T, $p < 0.01$) tasks across background exertion. RPD was significantly increased with both additional motor ($p < 0.01$) and cognitive ($p < 0.01$) tasks in both hand (5.23 ± 1.82 in HT, 3.77 ± 1.42 in HC, 2.08 ± 1.20 in H) and tongue (5.23 ± 1.82 in HT, 4.81 ± 1.83 in TC, 3.38 ± 1.63 in T) across background exertion, with the greater influence of the former than latter for hand ($p < 0.01$). The absolute error in the hand did not change with the cognitive task

(HC), but increased significantly by 108% with the concurrent tongue task (HT) (Figure 4A). In the tongue, the absolute error increased significantly by 16% with the concurrent cognitive task (TC), and further increased significantly by 47% with the concurrent hand task (HT) (Figure 4B). As a result, the absolute error during the concurrent hand and tongue task (HT) was significantly greater than the independent motor task (H and T) and the concurrent motor and cognitive task (HC and TC). Background physical exertion influenced the absolute error significantly in both hand and tongue (Figures 4C and 4D). The absolute error increased by 24% and 18% in the hand and tongue, respectively, under high compared with low background exertion. There was no significant interaction of task and background exertion on absolute error. The same trend was obtained for the statistical results in the RMS error (Figure 5). On average, the RMS error increased by 25% and 18% in the hand and tongue, respectively, under high compared with low background exertion. The correctness of the cognitive task was not influenced by an additional task or background physical exertion, although the average value during the concurrent tongue and cognitive task (TC) was much less compared with other tasks (Table 2).

In Part 2, heart rate, RPE and RPD were significantly higher during high compared with low background exertion across tasks (Table 1). While there was no significant effect of task on heart rate or RPE, RPD was influenced by task. Completing the task by tongue was rated with significantly higher RPD than by hand (3.54 ± 2.18 vs. 2.24 ± 1.56 , $p < 0.01$) across background exertion. The game score by hand or tongue ranged 57–430, the number of lives used ranged from one to six and completion time ranged 40–60 s. The game score and scoring efficiency were influenced significantly by task but not by background physical exertion (Figure 6). On average, the game score and scoring efficiency in the hand were 1.2 times and 2.9 times better compared with the tongue, respectively, across background exertion.

In Part 3, heart rate, RPE and RPD were significantly higher during high compared with low background exertion across tasks (Table 1). While there was no significant effect of task on heart rate or RPE, RPD was influenced by task. The RPD of shooting by tongue was significantly higher than by hand (4.65 ± 2.33 vs. 2.88 ± 1.77 , $p < 0.01$) across background exertion. There was a significant main effect of background physical exertion on both shooting error and shooting delay (Figure 7). Shooting error during high background exertion was greater by 59%, on average, compared with low background exertion across tasks. Shooting delay was decreased by 13% during high compared with low background exertion across tasks.

Discussion

The employed walking conditions produced different levels of background physical exertion as confirmed by the difference in both physiological (heart rate) and psychological (RPE) measures of exertion. The major new findings in the study are as follows: (1) tracking error of a slow waveform was increased with an additional motor or cognitive task for tongue, but only with an additional motor task for hand; (2) motor performance for slow waveform tracking and shooting with the left hand was compromised with greater background physical exertion in both hand and tongue for similar amounts; (3) motor performance for rapid and

accurate displacement was not influenced by the differences in the level of background physical exertion.

During slow waveform tracking (Part 1), an additional fine motor task increased the tracking errors in both hand and tongue (Figures 4A and 5A). This effect of an additional fine motor task is consistent with our previous findings during similar tasks without background physical exertion (i.e. in a rested sitting position). An additional cognitive task, in contrast, did not influence hand or tongue performance when performed without background physical exertion (Johnson et al. 2012). In the current study with background physical exertion, the tongue tracking errors increased due to an additional cognitive task (Figures 4B and 5B). These findings implied that degrading influences of an additional fine motor task are obvious on hand and tongue whether or not it accompanies background physical exertion, whereas degrading influences of an additional cognitive burden may emerge with the presence of background physical exertion.

Degradation of task performance with an additional concurrent task occurs most likely because the attentional resources allocated to one or more tasks are reduced when the attentional resources needed to concurrently perform multiple tasks exceed the total capacity (Kahneman 1973). Although a concurrent motor and cognitive task in sitting may not require attentional resources to a critical level that exceeds the availability (Johnson et al. 2012), an addition of walking might add an extra burden on the central nervous system to share its limited attentional resources. As a consequence, the influence of an additional cognitive task on the tongue performance may likely be altered. Since only tongue performance was influenced by the additional cognitive task in this study, it is likely that the tongue task required a greater amount of attentional resources compared with the hand task during the slow waveform tracking. The lower cognitive correctness in the tongue–cognitive task compared with the hand–cognitive task supports this interpretation. This result implies the tongue/TDS performance in accurate path tracking, such as navigating a wheelchair in fine space, may be potentially enhanced by improving the design of the graphical user interface to lower the cognitive burden on the user.

The level of background physical exertion significantly influenced the tracking errors in both hand and tongue in the slow waveform tracking (Part 1) (Figures 4C, 4D, 5C and 5D). Slow waveform tracking requires subjects to focus more on accuracy and less on speed. Accuracy is sensitively influenced by the level of background physical exertion likely because a greater level of physical exertion would require a greater amount of attentional resources against the hand or tongue task while imposing a greater amount of difficulties for stabilising the hand and tongue during walking.

The greater errors with a higher level of background physical exertion during the tracking task in Part 1 may be applied for interpreting some findings during the shooting game in Part 3. The shooting game required the left hand to displace and hold the cursor until the shooting command was initiated by the right hand or the tongue. Although not examined, potential greater displacement errors in the left hand may underlie significantly greater shooting errors with higher physical exertion without a significant difference between (right) hand and tongue (Figure 7A).

In the shooting task, subject performances were also influenced by the background exertion. They tended to shoot faster but less accurately when they were under higher physical exertion (Figure 7). The shooting task required coordination between two hands or between hand and tongue, and was considered as a multi-task assignment even without the add-on background physical exertion. The shooting task demanded a significant amount of attentional resources and therefore was more prone to the additional workload due to the further attention distraction from the additional physical exertion. There was no statistical difference in the shooting performance between using hand and tongue as the trigger. The comparable shooting performance implied that tongue might be a good substitute for hand/finger in completing trigger or initiation tasks such as shooting firearms under heavy load conditions when the hand and finger functions are not available, e.g. when engaging in other tasks.

Motor performance for rapid and accurate displacement in Part 2 was not influenced by the background physical exertion (Figure 6). Since the sizes of the red fish under subjects' control and the target fish were relatively large, this task required subjects to focus more on speed, while taking accuracy into account only when it was crucial. The task was relatively easier and required less attention compared with the ones in Parts 1 and 3 because subjects did not have to manipulate the cursor at all times and had a chance to rest when needed. They also had ample time to predict the target trajectory at the early stages of the game and move their fish in that direction. The relative easiness of the task is probably the reason why the performance of this task was less sensitive to the increase in the background exertion, i.e. there were enough attentional resources available for handling both the motor task and background exertion.

In both Parts 2 and 3, where a fair comparison between the hand and tongue performances is possible, the hand was superior to the tongue in accomplishing both tasks. According to the RPD, using tongue was always harder than hand for completing these tasks. More specifically, using tongue under fast walking was perceived to be the most difficult, and using hand during slow walking was the easiest. This difference in perceived difficulty could be due to the familiarity and prior experience of the subjects with playing games using their hands and a joystick compared with using their tongue and the TDS. Therefore, it is possible that the difference in perceived difficulty may change with more practice over a long enough period of using the TDS on a regular basis.

Conclusions

In conclusion, slow waveform tracking performance by the tongue was compromised with an additional motor or cognitive task, but with an additional motor task only for the hand. Additional background physical activity did not influence rapid and accurate displacement motor performance, but compromised the slow waveform tracking and shooting performances in a similar manner across hand and tongue.

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References

- Borg GA. Psychophysical Bases of Perceived Exertion. *Medicine and Science in Sports and Exercise*. 1982; 14(5):377–381. [PubMed: 7154893]
- Enoka RM, Christou EA, Hunter SK, Kornatz KW, Semmler JG, Taylor AM, Tracy BL. Mechanisms That Contribute to Differences in Motor Performance between Young and Old Adults. *Journal of Electromyography and Kinesiology*. 2003; 13(1):1–12. [PubMed: 12488083]
- Ghovanloo, M. Tongue Operated Assistive Technologies. *Proceedings of the 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*; 2007. p. 4376-4379.
- Hiraga CY, Garry MI, Carson RG, Summers JJ. Dual-Task Interference: Attentional and Neurophysiological Influences. *Behavioral Brain Research*. 2009; 205(1):10–18.10.1016/j.bbr.2009.07.019
- Huo X, Ghovanloo M. Evaluation of a Wireless Wearable Tongue–Computer Interface by Individuals with High-Level Spinal Cord Injuries. *Journal of Neural Engineering*. 2010; 7(2)10.1088/1741-2560/7/2/026008
- Huo, X.; Wang, J.; Ghovanloo, M. A Magnetic Wireless Tongue–Computer Interface. *Proceedings of the 3rd International IEEE/EMBS Conference on Neural Engineering*; 2007a. p. 322-326.
- Huo, X.; Wang, J.; Ghovanloo, M. A Wireless Tongue–Computer Interface Using Stereo Differential Magnetic Field Measurement. *Proceedings of the 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*; 2007b. p. 5723-5726.
- Huo X, Wang J, Ghovanloo M. A Magneto-Inductive Sensor Based Wireless Tongue–Computer Interface. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*. 2008; 16(5):497–504.10.1109/TNSRE.2008.2003375 [PubMed: 18990653]
- Johnson AN, Huo X, Ghovanloo M, Shinohara M. Dual-Task Motor Performance with a Tongue-Operated Assistive Technology Compared with Hand Operations. *Journal of NeuroEngineering and Rehabilitation*. 2012; 9(1)10.1186/1743-0003-9-1
- Johnson AN, Wheaton LA, Shinohara M. Attenuation of Corticomuscular Coherence with Additional Motor or Non-Motor Task. *Clinical Neurophysiology*. 2011; 122(2):356–363.10.1016/j.clinph.2010.06.021 [PubMed: 20638330]
- Kahneman, D. *Attention and Effort*. Englewood Cliffs, NJ: Prentice Hall; 1973.
- Kaluzny P, Palmeri A, Wiesendanger M. The Problem of Bimanual Coupling: A Reaction Time Study of Simple Unimanual and Bimanual Finger Responses. *Electroencephalography and Clinical Neurophysiology*. 1994; 93(6):450–458. [PubMed: 7529696]
- Kandel, ER.; Schwartz, JH.; Jessell, TM.; Mack, S.; Dodd, J. *Principles of Neural Science*. New York: Elsevier; 1991.
- Oldfield RC. The Assessment and Analysis of Handedness: The Edinburgh Inventory. *Neuropsychologia*. 1971; 9(1):97–113. [PubMed: 5146491]
- Shinohara M, Keenan KG, Enoka RM. Contralateral Activity in a Homologous Hand Muscle during Voluntary Contractions Is Greater in Old Adults. *Journal of Applied Physiology*. 2003; 94(3):966–974.10.1152/jappphysiol.008362002 [PubMed: 12433847]

Figure 1.

A subject using the TDS to perform tongue tasks. The major components of the TDS headset are depicted (A). The wireless control unit sits on top of the headset with the battery supply in the back. Two magnetic sensors are attached (one on each side) to detect the movement of the magnet on the subject's tongue (B).

Figure 2.
The experimental set-up: a subject wearing the TDS headset and holding the hand-held force measurement unit to perform a waveform tracking task while walking on the treadmill.

Figure 3.

Illustration of hand and tongue tasks: (A) Part 1: subjects used their tongue (T) and/or right index finger (H) to control the vertical position of a marker moving up and down to track a sinusoidal waveform; (B) Part 2: subjects used their tongue (T) or right index finger (H) to play a video game that required a rapid and accurate displacement and timing control of a computer cursor in a 2D space to catch or avoid moving objects; (C) Part 3: subjects used their tongue (T) or right index finger (H) concurrently with their left hand to play a video game that required a rapid and accurate displacement and timing control of a cross-hair computer cursor in a 2D space to aim at and shoot a randomly appearing target.

Figure 4.

Main effects of task and background physical exertion on the absolute error of hand and tongue during the waveform tracking task in Part 1. Note: H, independent hand task; T, independent tongue task; HT, concurrent hand and tongue task; HC, concurrent hand and cognitive task; TC, concurrent tongue and cognitive task. $**p < 0.01$.

Figure 5.

Main effects of task and background physical exertion on the RMS error of hand and tongue during the waveform tracking task in Part 1. Note: H, independent hand task; T, independent tongue task; HT, concurrent hand–tongue task; HC, concurrent hand–cognitive task; TC, concurrent tongue–cognitive task. $**p < 0.01$.

Figure 6.

Game score and scoring efficiency during the rapid and accurate displacement and timing control task in hand and tongue under different background physical exertion in Part 2. The scoring efficiency was calculated from the game score, number of lives used and time to completion as $\text{score}/(\text{lives} \times \text{time})$.

Figure 7. Main effects of task and background physical exertion on shooting error and shooting delay in Part 3. Note: Low, low background physical exertion; High, high background physical exertion; * $p < 0.05$, ** $p < 0.01$.

Table 1

Heart rate, rating of perceived exertion and rating of perceived difficulty in Parts 1–3.

	Heart Rate (beats/min)		RPE		RPD	
	Low	High	Low	High	Low	High
Part 1						
BL	100.5 ± 17.8	133.9 ± 24.2	0.77 ± 0.60	3.00 ± 1.53	1.15 ± 0.69	1.92 ± 0.95
H	101.8 ± 18.8	137.2 ± 28.1	0.92 ± 0.64	3.62 ± 1.56	1.54 ± 1.13	2.62 ± 1.04
T	98.2 ± 18.6	134.4 ± 19.7	0.77 ± 0.73	3.62 ± 1.61	2.54 ± 1.34	4.23 ± 1.26
HT	99.2 ± 20.7	132.6 ± 19.3	1.15 ± 0.80	3.85 ± 1.91	4.54 ± 1.33	5.92 ± 1.76
HC	103.1 ± 22.7	141.2 ± 23.6	0.92 ± 0.86	3.77 ± 1.59	3.15 ± 1.48	4.38 ± 1.66
TC	101.6 ± 17.7	142.3 ± 20.7	1.00 ± 0.71	3.69 ± 1.75	4.08 ± 1.61	5.54 ± 1.81
Mean	100.7 ± 18.9	136.9 ± 22.4**	0.92 ± 0.72	3.59 ± 1.63**	2.83 ± 1.80	4.10 ± 1.98**
Part 2						
H	102.8 ± 16.3	143.7 ± 27.2	1.23 ± 0.73	3.92 ± 2.06	1.08 ± 0.90	3.31 ± 1.25
T	101.9 ± 17.7	138.2 ± 22.1	1.38 ± 1.12	4.08 ± 2.29	2.23 ± 1.59	4.85 ± 1.91
Mean	102.4 ± 16.7	140.9 ± 24.5**	1.31 ± 0.93	4.00 ± 2.14**	1.68 ± 1.41	4.08 ± 1.76**
Part 3						
H	106.5 ± 18.2	138.3 ± 21.1	1.31 ± 0.85	4.62 ± 2.53	2.46 ± 1.66	3.31 ± 1.84
T	105.2 ± 19.1	138.3 ± 23.1	1.62 ± 1.76	4.77 ± 2.52	4.15 ± 2.30	5.15 ± 2.34
Mean	105.8 ± 18.3	139.7 ± 22.3**	1.46 ± 1.36	4.69 ± 2.48**	3.31 ± 2.15	4.23 ± 2.27*

Note: RPE, rating of perceived exertion; RPD, rating of perceived difficulty; Low, low physical exertion (level slow walking); High, high physical exertion (inclined fast walking); BL, baseline without any task (just walking); H, hand task; T, tongue task; HT, concurrent hand and tongue task; HC, concurrent hand and cognitive task; TC, concurrent tongue and cognitive task; Mean, mean value across tasks.

* $p < 0.05$ and

** $p < 0.01$ compared with low in the mean values (main effect of background physical exertion). See text for the effect of task.

Table 2

Cognitive correctness during different tasks and background physical exertion in Part 1.

	Task		
	C	HC	TC
Low	82.1% $\pm$ 22.0%	82.1% $\pm$ 22.0%	71.8% $\pm$ 30.0%
High	82.1% $\pm$ 29.2%	79.5% $\pm$ 25.6%	56.4% $\pm$ 31.6%

Note: Low, low physical exertion (level slow walking); High, high physical exertion (inclined fast walking); C, independent cognitive task; HC, concurrent hand and cognitive task; TC, concurrent tongue and cognitive task. No significant difference across tasks or background exertion.