Using the Jaw for a Human-Machine Interface Input Device - A Brief Review

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1 Introduction

Human machine interaction (HMI) is an important field in an age of humans interacting with machines and computers. It has applications in many disciplines such as equipment or robot control [1], prosthetics [2] and computer input. The term HMI broadly covers the topics of a machine's behavior, an intended task, a model of the machine's behavior understood by the user, and a physical interface between the user and the machine [3]. In this paper, we will discuss how and why the human jaw could be used for the physical interface (or input device) component of an HMI. For the rest of the paper, the term "HMI" will be used interchangably with "interface" to refer to this physical interface component.

The standard for input devices are hand interfaces, which directly map motion of a user's hand or fingers to some machine input. Hand interfaces are the interface of choice for desktop computers, machine control and direction control of vehicles; they are precise, fast and are intuitive for users. However, there are many situations in which hand input devices are not feasible:

- **Hand-Intensive Devices -** Machines such as sewing machines or pottery wheels require use of the hands in conjunction with machine operation. Handsfree input devices are required to control such machines while using them.
- **Supernumerary robotic limbs -** If a robotic arm is intended to augment a user's two existing hands, the hands cannot be used to control the arm.
- **Assistive technologies -** Some users of assistive technologies may not have control of one or both of their hands. Examples include tetraplegics desiring to use a powered wheelchair, robotic arm, or computer [4]; or stroke patients who find it difficult to control their hands.
- **Prosthetics -** Handsfree interfaces are well suited to controlling active hand or arm prostheses, where use of a hand interface may be impractical or impossible.

Motivated by applications like these, many researchers have studied input devices that do not require a user's hands. Some handsfree input devices interface with various parts of a user's body, such as their feet [5] [6], shoulders [7], tongue [8] [9], or voice [10]. Other systems tap into the bioelectrical signals in a user's nervous muscular systems [11]. Different methods of handsfree HMI lend themselves better to different use cases, an idea that will be discussed in more depth later in this review.

One handsfree HMI system that has not been studied extensively is jaw interfaces [12]. The human jaw has several attributes that make it attractive for use with a HMI, including precision [13], resistance to fatigue, proximity to the brain, potential for muscle learning [14], and potential for coordination with hands. Additionally, many systems currently exist in the medical field to track jaw motion and could be repurposed to provide input to a machine. [15]

In this paper we aim to review existing work in handsfree input devices, focusing on specific advantages and disadvantages of each system and how a jaw interface could address some of the disadvantages. We will explore what physical quantities of the jaw could be measured, and various methods that could measure those quantities. Finally, we will revisit common applications and discuss how the attributes of a jaw interface would enable it to be best used in those applications. It is intended that lessons learned from other handsfree input devices can be applied to further research on a jaw input device.

2 Motivation - A Brief Review of Existing Handsfree HMI

To motivate research of a jaw based HMI, we will first discuss previously researched handsfree HMI and their advantages and disadvantages.

2.1 EEG

Electroencephalography (EEG) is a method of measuring the brain's electrical signals and neural activity. EEG can detect voluntary neural activity from actions such as moving muscles [16] or from voluntary thought patterns [17]. Bioelectrical input methods like these tend to be noisy, and it is difficult to extract continuous inputs from them [18]. It has applications in brain-computer interfaces (BCI), biometrics, neuroscience, and other fields. [17]

EEG has the advantage of being widespread, with many commercial EEG sensors available [17], and lots of research exists on EEG signals and how to process them [18] [19] and their usage as an assistive technology. [17] On the other hand, since it is difficult to extract continuous signals from an EEG, their utility as HMI input devices is limited to applications that use discrete signals. Their utility as a HMI is further hampered by low ease-of-use; wet wired EEG devices, which provide the best accuracy when a user is in motion, use conductive gel pads that must be mounted by a trained technician [17, p. 2].

2.2 Tongue Control

Many methods have been researched to use the tongue as an input device for a HMI. Magnetic sensors detecting the motion of a magnet affixed to the tongue can distinguish multiple distinct tongue motions as individual commands ([8], [20], [21], [22]). Microphones in the ear canal can detect at least four distinct tongue motions [23]. The tongue can push buttons on a remote [24]. It can be tracked precisely using induction, allowing for continuous analog control [9]. EMG, EEG and skin deformation can be measured to detect the tongue contacting various teeth, which can provide 10 individual commands [25].

Tongue control has several advantages. The tongue holds a similar importance in the motor cortex as the hands, supporting its use for complex motions, and its muscle is resistant to fatigue [26]. However, outfitting the tongue for HMI use is an invasive technique. In several of the studies involving magnets mounted to the tongue, the magnets were connected to preexisting piercings [21] or the researchers recommended piercings for long term use [22]. This could be a deal breaker for users who do not wish to modify their bodies in order to use a machine interface, as well as a health issue if piercings or other tongue mounts are not maintained. Additionally, using the tongue with a HMI can interfere with mastication or vocalization during use.

2.3 Speech / Voice

While there are efforts on many fronts related to speech recognition, we only found one research effort that used the human vocal tract to provide a continuous input in multiple dimensions, a sort of "vocal joystick". Malkin et al. developed a software library that "[maps] nonlinguistic vocalizations into ... control signals." [10] They were able to control motion in two dimensions or three dimensions using vocal pitch and variations in assonant vocalizations [27]. They found that for 2D positioning tasks, their "Vocal Joystick" was more performant than verbal direction commands, similar in performance to a velocity joystick, and less performant than a computer mouse.

Vocal control shows promise as an inexpensive and accessible hands free HCI; it can be run on any computer with a microphone. However, it could suffer from major issues inherent to audio-based interfaces such as sensitivity to background noise or other users in the same space. Additionally, it may not be feasible to use nonlinguistic vocalizations in shared spaces where verbal communication is important [6].

2.4 Foot

Possibly the most mainstream handsfree input devices is foot control; there are many examples of foot input devices in the consumer market and in literature. Foot pedals are used to send precise continuous input to countless vehicles, musical instruments and machines such as sewing machines and pottery wheels. Foot control is commonly used in medical devices, and advanced continuous foot inputs for medical devices have been researched [6]. Foot control has also been researched as a method of controlling supernumerary arms in more than one dimension; Dougherty and Winck demonstrated improvement in task performance when assisted by a supernumerary arm controlled by a 2 axis planar foot interface [5].

Foot input devices have several advantages and disadvantages. As Hatscher and Hansen noted, they are already commonly used for 1D proportional control in medical devices, so more advanced foot input devices may be easily learnable [6, p. 152]. Usage of the foot is often not required for seated tasks, so for such tasks there is no lost function by using the foot to control something.

However, the foot and leg can suffer from fatigue when doing motions for long periods of time, a limitation noted by Dougherty and Winck [5]. In their study comparing performance of individuals using just a hand interface to complete a task with those using both hand and foot interfaces, the latter group reported a high physical demand associated with moving their foot. Another disadvantage is that use of the foot for an input device is more difficult when the user is walking around, as mobility must be distinguished from control inputs.

2.5 Eye

Tracking eye motion can be used to provide machine input, and has been researched extensively for human-computer interfaces. As early as 1991 several researchers had found that eye tracking allowed for cursor positioning about twice as quickly as existing cursor positioning devices, and many more systems existed to track eye motion for medical purposes [28]. These systems can be targeting systems, which involve a graphical user interface with targets that the user looks at to interact with them [29]; or they may use a direct control approach, where two dimensions of eye movement are mapped directly to machine inputs.

Eye input has many advantages. Firstly, eye tracking methods are abundant, cheap, and easy to use. Krafka et al. have developed a machine learning dataset and model that can achieve state-of-the-art accuracy tracking gaze with an inexpensive video camera [30]. This level of development using commonplace hardware makes it very accessible for both researchers and companies looking to implement eye tracking input into their products. Secondly, for large enough targets, eye tracking can be significantly faster than manual pointing methods [31, p. 48].

Eye tracking input also has several downsides that make it difficult to use in some applications. Firstly, as noted by Majaranta and Bulling, it can be difficult to measure where the user is looking; there is a small area at the center of a user's vision that is seen in detail, and a user could be focusing on anything in that area without moving their eyes voluntarily. They also note that visual eye tracking systems tend to drift over time, due to varying lighting and pupil size [31]. Additionally, visual feedback cues (which can be important for many HMI applications) are more difficult to implement with eye tracking, since the user cannot look in an arbitrary direction for feedback.

2.6 Head Motion

Motion of the head shows promise as a handsfree HCI and has found commercial application. It can consist of measuring head position or by using the head to physically move a joystick. Williams et al. successfully used head motion to control an arm in 3D space. They tried two methods: directly measuring head orientation and measuring EMG on the neck and head muscles, and compared each method's performance to that of a joystick. They noted that users tended to use a "sequential command strategy" where motion was controlled one dimension at a time, which had a different effect on each method's performance [32]. Kutbi et al. tracked head position using computer vision in order to control motion of an electric wheelchair. A virtual joystick on a screen provided feedback to the users of what command they were giving the wheelchair. They found that optical head tracking was slower than both thumb joystick and a chin operated joystick, but that it improved with practice [33]. Head motion has been used in commercial products; Munevo DRIVE is a head-mounted inclination sensor that can be used to operate electric wheelchairs and robotic arms using head motion. Munevo's research study found that their system had lower throughput than a joystick, but was comparable in driving errors [34] [35].

Head motion has a few advantages; it is intuitive and easy for new users to learn, having performance in 3D positioning tasks only slightly inferior to a hand joystick [32]. The main disadvantage of head motion is the opportunity cost of using it for computer input; head motion input can interfere with tasks requiring the user to look around at the task they are completing. Much like eye control, this can be an issue for HMI systems where visual feedback is required.

2.7 Upper Body Motion

Tracking the shoulders in addition to the head can add more degrees of freedom to work around some of the disadvantages of head motion. Fall et al. used 3 inertial measurement units (IMUs) to track the roll/pitch of a user's head and vertical displacements of shoulders. To control a robotic arm, roll and pitch of the head were mapped to for-backward and left-right translation of the arm and right and left shoulder displacement were mapped to up-down translation of the arm [36]. Fall later went on to conduct experiments on a more sophisticated upper body motion tracker that measured both positions with IMUs and muscular activity with EMGs [37]. Seáñez-González and Mussa-Ivaldi also placed IMUs on the upper body, and were able to use Kalman filtering to intuitively map upper body movement onto 2D cursor movement [38]. Thorp et al. used principal component analysis (PCA) to map eight dimensions of shoulder movements to two continuous inputs for controlling an electric wheelchair. They found that users were generally slower at navigating with shoulder input than with joystick input [7]. Casadio et al. used vision targets to track shoulder and upper arm movements, and also used PCA to map this high dimensional space onto 2D cursor movements. They found that users over time reduced upper body movements that did not affect cursor movements [39].

Using the shoulders to augment head motion can add extra degrees of freedom to the input, but with the disadvantage of tying up additional body parts for the interface. In the context of supernumerary arms, gathering input from shoulders and upper arms is impractical since the user's arms are already being used directly to perform the task at hand.

2.8 Summary

In summary, many handsfree HMI input devices exist that allow users to provide machine input using various parts of their body. They all have advantages and disadvantages, especially in context of specific applications. A tradeoff that seems to appear when choosing an input device is input performance or opportunity cost of use; body parts that are used commonly for motion tasks (eyes, tongue) tend to have higher input performance. Using these body parts for HMI input precludes using them for their original tasks. The next few sections will make a case for researching use of the jaw as an HMI input method, as the jaw has attributes that could let jaw-based HMI input circumvent the downsides of many other handsfree HMI input methods and work uniquely well for certain applications. The following table summarizes the above points for each mode of HMI input.

Table 1: This summary table compares existing modes of handsfree Human-Machine Interface (HMI) with respect to availability, performance, fatigue, interference with other functions, and other factors.

Existing HMI Mode	Availability	Performance	Fatigue	Interference with other functions	Other	Examples in Literature
EEG	Readily available	Noisy, Discrete signals	Medium			[16], [17], [18], [19]
Tongue	Not very accessible	High importance in motor cortex	Low	Mastication, vocalization	Physically invasive	[8], [9], [20], [21], [22], [23], [24], [26], [25]
Speech	Accessible, inexpensive	Middling performance	Low	Vocalization	Sensitive to environment	[6], [10], [27]
Foot	Widespread, readily available		High	Walking	Very intuitive	[5], [6]
Eye	Widespread, accessible	High speed, low precision	Low	Visual perception		[28], [29], [30], [31]
Head Motion	Accessible	Comparable to joystick	Medium	Visual perception	Intuitive	[32], [33], [34], [35]
Upper Body	Somewhat accessible	many degrees of freedom, slower than joystick	Medium	Arm usage	Intuitive	[7], [36], [37], [38], [39]

3 Attributes of a Jaw Interface

The human jaw, its joint (the temporomandibular joint), and its muscular system have many properties that are favorable for use as a human machine interface and may be particularly well-suited for certain applications. Here we will present several properties of the human jaw system and how they relate to HMI usage, and what applications they might be useful for.

3.1 Precision

The human jaw must have very precise motions for normal activity such as talking and eating [13]. The jaw's resting position and the path it takes while chewing must remain constant, in order for occlusion (how the teeth contact and fit together) to be correct [40]. To achieve correct occlusion, the jaw's precision is much higher when the jaw is nearly closed [41]. If the jaw's motion can be repeated precisely, inputs from a jaw-based HMI would be repeatable, which would make it easier to learn and use the HMI.

3.2 Disturbance Rejection

The jaw has built-in mechanisms to keep itself stable and resist motion when acted upon by disturbances. Miles et al. found that the jaw's muscles have inbuilt reflex responses to being stretched, allowing them to resist external forces with very low latency [42]. This property could make a jaw interface uniquely suitable for applications where the user is in motion and/or jostled around, such as vehicle control or standing and moving applications.

3.3 Motor Training

Several studies have suggested that the muscles of the jaw are responsive to motor training. Chen et al. found that the jaw increased its precision in a positioning task more than the finger did when given the same amount of training. One could argue that this is simply a case of the fingers already being trained, but the authors claimed that the result pointed to a fundamental difference in how the two motor systems were controlled and actuated by the brain [14]. Ability to be easily trained is a positive attribute for any application, since all applications of a jaw interface would require some training period.

3.4 Fatigue

Human vocalization and facial communication involves a large amount of repetitive motion in the sagittal plane. Humans perform these motions many times a day, often for long periods of time, without fatiguing the muscles involved with jaw motion. It therefore follows that the jaw muscle system is resistant to fatigue when moved without resistance. This is an advantage for use with an HMI for long periods of time without discomfort.

On the other hand, some jaw actions can be incredibly fatiguing, especially the clenching action required to trigger EMG systems. As Calhoun and McMillan note, repeated jaw clenching to command an EMG based HMI can result in fatigue and can have negative effects on existing jaw dysfunction or injuries [43].

3.5 Coordination

Newborns explore the world mouth-first, gradually transitioning to use of their hands as their motor skills develop. However, humans retain a strong connection between our mouth and hands through adulthood. Often times, when concentrating on performing precision tasks, people will unconsciously press their tongues against their lips or move them in sync with their hand motions [44]. This connection between the mouth and hands could have special relevance to an HMI for a machine designed to be used *with* the hands, such as a supernumerary arm; users may learn very quickly how to supplement their hand movements with mouth movements since the neurological framework to do so is already present. It is also possible that this framework makes it harder to decouple hand and mouth movements, making it more difficult to perform some tasks with hand movements and a jaw based HMI.

3.6 Ergonomics

Without specifying a specific method of tracking jaw motion, it is difficult to make a claim about the ergonomics of a jaw interface. As will be discussed in Section 4, many existing methods of tracking jaw motion for medical purposes involve some form of headgear [15]. Headgear tends to be more invasive than hand interfaces such as joysticks, but could be designed to be as ergonomic as commercial headgear products such as headphones [45]. Some require placing a sensor inside the mouth (most notably the Siemens Sirognathograph [46]), which is just as invasive and inconvenient as tongue interfaces. However, unlike the tongue, it is also possible to track jaw motion visually with an external camera. There is a wide range of implementation-specific factors that could play into the ergonomics of a jaw HMI.

3.7 Disruptiveness

Just as using a hand interface precludes use of the hand for a task, use of a jaw interface can impede on a user's ability to use their jaw for tasks such as speaking and eating while they are using it to communicate with a machine. This could be problematic for tasks where a user must vocalize or communicate with other users while working, such as a shared manufacturing environment. As with ergonomics, there is a wide range of implementation-specific disruptiveness factors.

3.8 Summary Table

In Table 2, we summarize the properties of the human jaw that relate to usage with a HMI. Each property is organized into favorable and unfavorable attributes and compared generally to existing handsfree HMI input devices.

Table 2: This table summarizes the properties of the human jaw and how they relate to an HMI input device.

Jaw Property	Favorable Attribute	Unfavorable Attribute	Comparison to Existing Handsfree HMI
Precision	High positional precision in certain positions [41], high force precision when closing [42]		Possibly less precise than finger motion
Stability	Built-in reflexes for resistance to disturbances		Upper body, head, and foot control would be more susceptible to external disturbances. Enclosed structures such as tongue or eyes could be less susceptible.
Motor Training	High ability to learn tasks		Showed higher rates of motor learning than the finger [14]
Fatigue	Low fatigue for small motions near resting position	High fatigue and risk of damage when clenching [43]	Generally less fatiguing than foot interfaces, head motion and upper body control
Coordination	Potential for coordination with hands		The eyes are also clearly coordinated with the hands. Most other body parts are less clear.
Ergonomics			Both comfortable, ergonomic systems and uncomfortable, invasive systems could exist, as opposed to tongue HMI which is entirely invasive.
Disruptiveness		Precludes use of mouth (eating, speaking) while using HMI.	Similar to tongue interfaces, a jaw interface could interfere with speaking and eating. Other interfaces interfere with other actions.

4 Prior Art in Jaw HMI

Having discussed the positive and negative attributes of using a jaw input device for HMI, we will explore existing work in the area. Jaw input devices have not been researched extensively; we found several research efforts measuring discrete signals from the jaw, but none measuring continuous input for HMI usage; this section will briefly overview existing research and motivate the need for continuing research in this area.

Yaslam and Feron claimed to be the first researchers using the jaw's position directly as input to an HMI. Their interface measured discrete boolean inputs (i.e. a button), and they compared response time of the jaw to that of the thumb. They found that the response time of the jaw was slower than the response time of the thumb, but that the jaw's response time improved with repetition more than the thumb's did [12].

Costa et al attempted to read multiple states of input from the jaw by measuring multiple states of clenching. They combined concepts from EEG and EMG, using EEG to read voluntary signals produced by clenching the jaw muscles. They were able to read five distinct states: soft and hard clench for each side of the jaw, and the relaxed state. In order to control multiple dimensions of motion, they implemented a state machine that used soft clenches to control motion in a dimension and hard clenches to change dimensions [16]. Chin and Barreto [47] and Barreto et al. [11] did a similar study, but augmented jaw clench detection with eyebrow motion detection and used EMG instead of EEG. Their system did not distinguish between soft and hard clenches. In order to control 2D position, they had raising and lowering eyebrows control motion in one dimension and clenching left and right jaws control motion in a second dimension.

This is a thin sliver of the research necessary to ascertain the feasibility of a jaw HMI input device. All of the above jaw HMI research studied discrete inputs, but continuous inputs are also important to study as they could perform better or worse [48] [49]. While a quick reaction time to a visual stimulus (feedback, as studied by Yaslam and Feron [12]) is important to handle anomalies when controlling a machine, it is the precision and repeatability of commands which allow a human to path plan quickly and precisely (feedforward). Therefore, further research is needed to study the performance of a HMI that can read continuous signals from the jaw in multiple dimensions.

5 Implementation

Having motivated the need to research jaw inputs for HMI, we will discuss avenues for future research, focusing on the measurands of the jaw and potential methods of measuring them.

The main jaw quantities that can be measured are muscle activity, positional displacement, and force. Each has trade-offs and are better suited for different applications and different methods of measurement. This section contains a discussion of each jaw measurand, each followed by a description of various systems that could measure it.

Muscle Activity

The jaw has several muscles including the masseters and temporalis [50] whose activity can be controlled by a user and measured or estimated using EMG or EEG. These technologies can detect one or two discrete states per individual muscle. As such, they are well suited for issuing preset commands or controlling systems with discrete inputs.

Muscle activity is typically measured directly using EMG (à la Barreto et al. [11]), the implementation of which can be finicky and dependent on the specific user. Generally, EMG works by attaching electrodes to the surface of a user's skin, which detect firing of muscle fibers [43, p. 120]. It can be difficult to distinguish between more than one level of muscle activity, let alone measure a continuous input; early EMG operated on thresholds for two states of control input [51]. Costa et al. provide an exemplar of detecting multiple jaw states by measuring muscle activity [16].

Position

The positional displacement of the jaw can be directly and continuously controlled by the user in in three directions or around three axes [52] which makes position an excellent candidate for HMI tasks requiring continuous input in multiple dimensions. Additional benefits include the jaw's high positional precision (discussed in Precision) and possible similarities to hand displacement, which is currently the gold standard of HMI. Yaslam et al. describe a discrete version of jaw position HMI measuring reaction time [12], but additional research is required in the area of 3D continuous inputs.

Measurement systems for jaw position have been studied in depth for use in medical fields. For example, a prosthodontist must be able to measure multiple static jaw positions precisely in order to design dental prostheses [53]. Jaw position measurement systems fall into several main classes:

- Physical
- Photographic
- Radionuclide
- Time-of-flight
- Magnetic/Electromagnetic

Physical

HMI devices can physically contact the jaw to measure its position. Madhavan et al. describe the facebow, an externally mounted medical instrument that physically contacts the jaw in several locations to measure its stationary position [15]. In his technical note on the Cybermouse 3D position measurement device, Prinz discussed attaching linear potentiometers to an elastic band on the chin, but provided little in the manner of schematics or attachment details. If a device measures movements of the jaw by interfacing with the chin, skin movement may cause a difference in measured vs actual mandible movement; Prinz discussed a method of measuring this deviation but did not present findings from using this method [46].

Photographic

It is possible to track position photographically using several methods. Early systems used photographic plates to track the position of strobe lights physically attached to the jaw [15]. Newer versions used video cameras, again to track markers designed to be visible on camera [15] [54]. More advanced systems can use computer vision techniques to estimate jaw position based on cameras pointed at the face [55]; some work has been done to account for motion of the skin over the jaw [56]. similar tasks have been performed for head motion [33] and eye tracking [30] [29]. Optical flow has been used to

Radionuclide tracking

As with other areas of the body, it is possible to track the position of radioactive markers attached to the jaw. Salomon and Waysenson placed a radioactive source in a tooth cavity and tracked its position accurately with a gamma camera [57] [58]. While this method is unlikely to be feasible for general purpose HMI, it shares technology with photographic tracking methods.

Time-of-Flight

The speed of sound and light waves in Earth's atmosphere is known precisely, so time-of-flight can be measured to find the distance from a sensor to an object. Optical or ultrasonic distance sensors could measure the position of the jaw or a target attached to it based on time-of-flight from known fixed positions. J. F. Prinz described attaching a commercial ultrasonic time-of-flight system (called the Cybermouse) to the jaw to measure its position with promising results [46].

Magnetic/Electromagnetic

Another noncontact method of measuring jaw position is magnetic sensors. These use the magnetic fields generated by magnets or within coils to measure position. The most commonly cited example in literature is the Siemens Sirognathograph, which uses magnetometers to detect the position of a magnet affixed to the teeth [46]. Alternate methods could use hall effect sensors. Another invasive yet popular technique is electromagnetic articulography, which uses electromagnets to induce current in small sensors mounted to oral structures [59].

Force

The force applied by the jaw can be directly controlled by the user, and multiple studies have examined the accuracy of humans attempting to provide a target bite force [60] [61]. While force control tends to be inferior to position when controlling position for both feet and hands, the jaw is innervated differently than the hands [14] and performs a fundamentally force-focused task [42] so it may exhibit better performance.

Measurement systems for jaw force are most developed for measuring bite force, but this is only one direction among many directions of force that the jaw can produce. [62]

In order to measure jaw force, there must be something for the jaw to apply force to. Closing forces could be measured inside the mouth using a force transducer mounted between the upper and lower dental arches; the transducer can measure forces applied upwards by the jaw against the upper dental arch. Downwards force, protrusion force and horizontal force could be measured from the outside using headgear that holds the jaw rigidly from those directions. Measuring force in the retrusion direction would be more difficult, as there is no outer surface on the jaw normal to that direction.

Other Structures

While it's possible to measure several attributes of the jaw directly, movement of the jaw can also cause changes in other bodily structures—these can also be measured and used for HMI. One such body structure is the ear canal; Bedri et al. were able to create an interface that detects changes in lower jaw position by measuring movement inside the ear canal. [45] Busch et al. achieved similar effects with a system that measured ear canal pressure. [63] Methods like these have the advantage of being noninvasive and unobtrusive, but may lack the precision and continuous inputs offered by position or force control.

6 Applications

Having described possible implementations of a jaw-based HMI input, we will discuss applications where certain implementations would excel and could fill gaps left by other HMI input devices. A summary table of implementations and applications is below, followed by an in-depth discussion of each possible application.

Table 3: This table summarizes the possible measurands of the jaw, methods to measure them, and potential applications.

Measurand	Measurement Methods	Applications
Muscle Activity	EMG ([11], [16])	Discrete inputs, preset commands (Text input/selection, mode selection, machine steering, accessible computer input)
Position	Physical ([15], [46]) Photographic ([15]) Radionuclide Tracking ([57], [58]) Time-Of-Flight ([46]) Magnetic/Electromagnetic ([46], [59])	Controlling physical motion (SRL control, machine control, standing machine control)
Force	Bite Force ([60], [61])	Force modulation applications (SRL end effector, some machine operations)
Other	Ear Canal Sensors ([45], [63])	Minimally invasive, discrete inputs (Active lifestyle / mobile computers)

6.1 Machine Operation - Standing

One area where handsfree HMI is useful is general machine operation, where the machine requires use of the hands (e.g. pottery wheels, sewing machines, TIG welding supplies) or the user needs more inputs than can be provided by the hands alone. Typically, machines like these use foot pedals as the handsfree input device [64], which precludes standing up and walking around. A jaw interface could be worn while walking around a machine and workpiece, offering new ways of interacting with larger work areas and improved productivity. The specific implementation will depend on the input type needed for the machine.

6.2 Supernumerary Robotic Limbs

Another use case where jaw HMI could excel is the use of supernumerary robotic limbs (SRL), due to several previously mentioned attributes of the jaw. Firstly, the jaw's high precision and ability to be continuously controlled is advantageous for position control tasks such as SRL control. Secondly, the jaw's natural coordination with the hands could make it intuitive for tasks involving a supernumerary limb working alongside a user's hands. Finally, a jaw input HMI would not preclude the user from walking around, allowing the user to stand and move around their workspace while controlling the SRL.

The recommended implementation for supernumerary robotic limb control is a physical position detection system with some form of force feedback proportional to the jaw's distance from a centered position. Physical position tends to outperform force or when used with an HMI to control position or velocity, as is required for moving a SRL [65].

If the supernumerary arm task is a gripping task or one requiring force modulation, it may be beneficial to instead use force control, as this is the most direct mapping from the user's input to the modulated quantity.

6.3 Vehicle Control

Most vehicles use foot pedals as a handsfree HMI, often to control vehicle acceleration or velocity while the hands control steering [64]. A jaw HMI may be suitable for controlling extra implements (such as a front-end loader) or as an accessibility option for users lacking foot or hand function.

The majority of research in the area of vehicle control with the jaw is based on EEG. Gomez-Gil et al. showed that it's possible to control the speed of agricultural equipment by using EEG signals tied to the jaw [66]. Wei and Huosheng had users successfully drive an electric wheelchair using EEG signals from a combination of jaw clenching and winking [67].

These EEG methods perform worse than the hand or foot position based HMI typically used to control these machines, possibly due to their inability to provide continuous input. A better option for vehicle control would be position or force control. Vehicle design has converged on using joysticks or steering wheels to steer vehicles, both of which are position control methods. Many such devices have springback proportional to the force applied, which makes them more similar to force control. Guo et al. discussed the advantages of force control and proposed a design for a chin-operated force control joystick for controlling wheelchairs. [68]

Multiple studies have discussed using a chin joystick to control power wheelchairs and actuators on them to great effect; however, these chin joysticks primarily require head motion to actuate, so it is difficult to ascertain the role of the jaw in these.

6.4 Accessible Computer Input

Computer usage is necessary for many people in modern society, but personal computers generally require hands to operate them. This is a problem for tetraplegics, amputees and others who cannot use their hands to operate computers, and a computer input device that does not require the hands to access the full functionality of computers would greatly benefit them.

To solve this problem accessible computer inputs have been studied, leveraging eye tracking, EEG, or other handsfree HMI to provide cursor inputs. While no research efforts have used the jaw directly as a computer input device, commercial products exist that take advantage of the mouth to operate a joystick with sip/puff sensors for 2D continuous motion and several discrete inputs. [69]

General computer use requires a pointing device, which is a 2D position control problem. A position-based jaw HMI would likely perform the best for this task, where jaw position would be mapped to pointer velocity. If the precision of the jaw is high enough and the range of measurable motion is big enough, jaw position could be mapped directly to pointer position, which has been shown to perform better in position tasks than mapping position to velocity. An optical system with an easily donnable tracker would minimize the amount of hand assistance needed to use the HMI.

7 Conclusion

A jaw-based HMI input device has the potential to fill gaps in the existing realm of handsfree HMI devices. Notable applications include supernumerary robotic limb (SRL) control; controlling machines where a user must walk around and use their hands whilst controlling the machine; controlling vehicles without use of hands or feet; and accessible computer input allowing tetraplegics, amputees, or other people without use of their hands to interact with a computer. However, very few researchers have examined jaw-based HMI input devices, and there are many questions left to answer. It is recommended that future research create a position-based jaw input device that can measure jaw displacement in three dimensions, and evaluate it using standard input device performance evaluation procedures.

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