A User-Centered Ergonomic Keyboard Design To Mitigate Work-Related Musculoskeletal Disorders

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Abstract

Work-related musculoskeletal disorders are amongst the most prevalent occupational disorders around the United States [1]. Acknowledging ergonomic variables, such as the architecture of workplace computer equipment, may well reduce the likelihood of employees forming musculoskeletal disorders [2]. This work portrays what we understand from research regarding the impact of workplace ergonomic interventions as it relates to the computer keyboard. Classic QWERTY computer keyboard designs are no longer constrained to the conventional horizontal configuration that are ordinarily packaged with individual computers. Now, there are keyboards which are partitioned into two sections, and these haves can have keys oriented at an angle, sloped down to the visual display terminal, or tilted up forming a geometric triangular shape [3]. These interventions are intended to position upper limbs in a more natural orientation resulting in pain alleviation, and a reduction in likelihood of musculoskeletal disorder development from the repetitive use of conventional computer keyboards [1]. Research efforts reviewed in this work also illustrate that experienced typists quickly adapt to alternative keyboard features, and are just as productive in terms of words per minute output. A proposed ergonomic computer keyboard design (Trinity) delivered in this paper maintains the integrity of literature by integrating insights from previous works to reduce musculoskeletal disorders while maintaining interactive user productivity.

Keywords: Ergonomic Keyboard, MSD, Trinity Design, RSI, Keyboard Design.

1. INTRODUCTION

This section introduces repetitive strain injuries and musculoskeletal disorders and the impactful implications these ailments have on industry.

1.1 Background

Repetitive strain injuries (RSI) are a group of disorders that result from repeated movements affecting the muscles, tendons, joints, and nerves. Ergonomic stressors such as recurring or strong dynamic movements and contortions have been correlated with RSI's. Such injuries lead to serious pain, loss of productivity, and even disability which lasts for months or years [4]. Unlike other injuries, RSIs develop over a prolonged period of time [5]. Because of this, warning signs are often neglected, therefore, in order to mitigate RSI's, it is crucial to incorporate primary prevention interventions early. In general, symptoms are easier to address, for if they become full Musculoskeletal Disorders (MSD's), they can become expensive and take a long period of time to treat. The liability of RSI's on affected individuals in addition to society is undoubtedly costly. One third of the compensation costs for workers in the US private industry are attributable to RSI and the direct compensation costs exceed US $20 billion [6]. According to the U.S. Bureau of Labor Statistics, over 26,000 Carpal tunnel syndrome (CTS) cases involving days away from work, showing a median of 25 days away from work. [7]. A rise in MSDs in white collar occupations has encouraged research efforts focused on incorporating appropriate ergonomic design interventions in office workstations which have been found to effectively reduce the risk of MSD symptoms. Productivity and efficiency decrease for workers who suffer from musculoskeletal symptoms [8].

1.2 Evidence for an Ergonomic Keyboard

A comprehensive review of literature regarding the affiliation between the use of computer keyboards and MSD incidents determined that keyboard-related MSDs is significant when computer keyboard usage greater than 15 hours per week [3]. This is attributable to the various uncomfortable positions of the hands and forearms required by end user in order to operate the keyboard simply due its lateral orientation. The forearm is forced in an unnatural pronated position such that the palms are parallel to the plane of the keys. Due to the dimensions of the keyboard structure, in addition to the requirement for "the hands to be near each other to place the fingers on the home keys while typing, mandate that both wrists be deviated in the ulnar direction" [3] as shown in Figure 1.

FIGURE 1: An aerial view of a women's hand using a conventional laptop keyboard requiring wrist ulnar deviation and forearm pronation [25].

Gerr and his colleagues concluded when users actively interact with keyboards for more than 15 hours per week, the likelihood of upper extremity musculoskeletal disorder symptom occurrence is significant [9]. Ergonomic computer keyboard designs can mitigate causes of musculoskeletal disorders including: flexor and extensor tendonitis of the digits [9], wrist deviation which is correlated with upper extremities, as well as electromyography (EMG) activity of the forearm musculature [10]. This paper will explore previous and current design interventions that have been integrated onto a computer keyboard which contribute to reducing MSD's. This work also discussing other critical design features that are required for long term adoption including comfort, productivity, and learning compatibility. Finally, this paper will introduce a user-centric ergonomic design based on the design components of previous ergonomic keyboards. The rest of this research is organized as follows: In Section 2, background and related works are reviewed.

Section 3 explains the design framework and introduces Trinity, the ergonomic keyboard design. Finally, Section 4 concludes the thesis and talks about future work.

2. LITERATURE REVIEW

This section introduces relevant terminology, design methods that were incorporated into alternative keyboards, as well as the effectiveness of these designs as they relate to mitigating MSD's while also attempting to maintain interactive user satisfaction.

2.1 Reducing Musculoskeletal Symptoms and Disorders while Maintaining Productivity

"The Effect of Alternative Keyboards on Musculoskeletal Symptoms and Disorders" by Moore and Swanson, one of most prominent studies of ergonomic keyboard use, "assessed whether keyboard design was directly linked to the risk of musculoskeletal disorders and symptoms" [2]. This research endeavor included 289 participants, who, for two years, leveraged: a standard keyboard, an adjustable split keyboard, or a fixed split keyboard for their daily computer use [2]. The study concluded, "In terms of primary prevention, only the fixed alternative keyboard demonstrated a significant effect on the incidence of musculoskeletal symptoms." It also discovered that the fixed split keyboard intervention mitigated impacting factors which prevented exacerbation for those distressed individuals who were experiencing a musculoskeletal disorder. Furthermore, a follow up to the longitudinal study in 1999 [11] determined that not only were alterative ergonomic keyboards effective in preventing MSD escalation, users were just as productive with the ergonomic design as they were with a conventional standard keyboard.

2.2 Improving Comfort and Efficiency for Computer Keyboard Users

In "Ergonomic Principles Applied to the Design of the Microsoft Office Computer Keyboard", Hugh McLoone and Ken Hinckley are concerned about improving comfort and efficiency for operators while using computer keyboard by providing several shortcut keys and modifying the keyboard layout. 30 participants were surveyed for their opinions on 127 variables on the keyboard, including new keys for single step operations. After obtaining a clear direction about the keys to use, an evaluative iterative study was carried out, which included comprehensive revision, assessment, and implementation of each new key and feature. In addition to these features, a wrist pad was provided which has demonstrated to thwart health issues induced by long term use as seen in Figure 2 [12].

FIGURE 2: Final design of McLoone and Hinckley's Microsoft Office Keyboard.

Major criticisms of their design is that there are too many keys, leading to compromises with key size and their relative spacing made by designers. Users with medium and large hands find it uncomfortable to use this keyboard. Along with small key size, the size of the text on the key is small as well, which causes visual stress. Regardless of these shortcomings, this design encouraged a natural hand and wrist position while typing reducing cumulative trauma disorders in those areas.

2.3 Ergonomic Keyboard Design Interventions

One recurring design feature that is frequently implemented into modern ergonomic keyboards is related to dividing the conventional layout of keys as shown in Figure 3. As described by Marklin et al. “The alphabetic segment of keys will be split down the middle, along a break line formed by the 7, Y, H, and N keys, which are in the right half” [3]. The slant angle, as shown in Figure 3, “is half of the horizontal opening angle of a split keyboard. The slope angle, which is the angle of the plane of keys on the keyboard is either angled upward, horizontally, or downward towards the visual display terminal, and the tilt angle is the angle that each half forms to the horizontal plane along the keyboard’s longitudinal axis.” Marklin’s et al. comprehensive review stated that while slant and tilt angles required a keyboard be split into two halves, the slope angle could be integrated while maintaining a conventional keyboard’s intact design. Design interventions slope and tilt are illustrated in Figure 4.

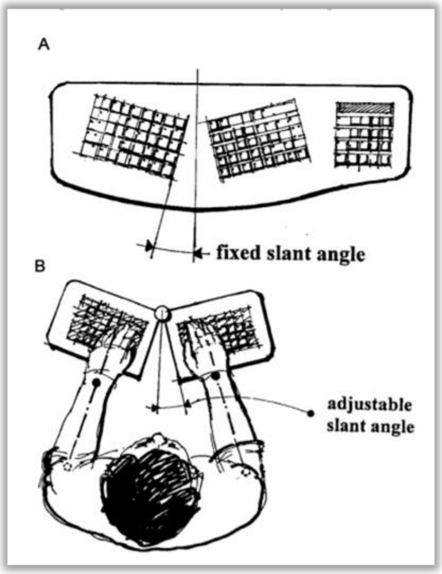


FIGURE 3: Sketch of a fixed-angle split keyboard (A) and an adjustable-angle split keyboard (B).

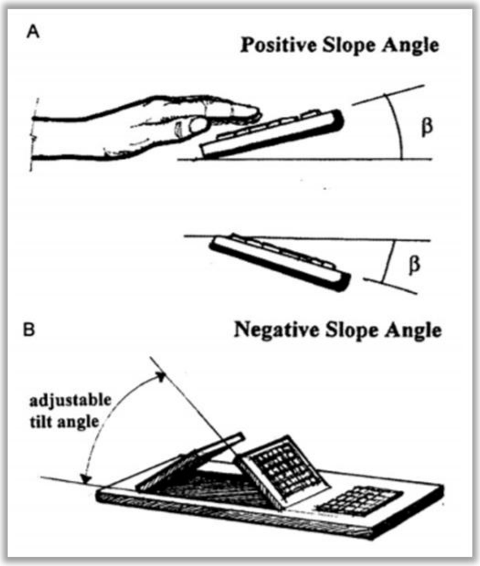


FIGURE 4: Illustration of a positive slope, negative slope, and an adjustable-tilt angle keyboard Illustration of a slope angle of a QWERTY keyboard (A) and an adjustable-tilt angle keyboard (B).

Marklin et al. studied various degrees for these angles in order to discover optimal orientations to mitigate RSI's [3]. According to their review: "It is specifically hypothesized that (1) incorporating a slant angle in the design of the keyboard will reduce wrist ulnar deviation, (2) incorporating a slope angle will reduce wrist extension, and (3) incorporating a tilt angle will reduce forearm pronation." Marklin et al. findings also concluded that while leveraging these angles would be advantages in mitigating musculoskeletal disorders, they alone may not be desirable enough to result in wide adaptation from users. One discovery was that providing the user with adjustable configurations to customize their keyboard experience "comes are the expense of confusion and/or frustration" through the trial and error process for user unfamiliar with the product. The following sections will delve into each angle, and will discuss their respective effective orientation, their impact on reducing MSD's, and user feedback in regard to comfort, productivity, and/or learning curve.

2.3.1 Learning Curve and Productivity

One of the main concerns of the ergonomic keyboard designers and manufacturers is the learning curve of the novice users and the continual compatibility of the keyboard with users. This is the main factor motivating many designers to turn towards ergonomic keyboards, as the learning susceptibility is shown to be excellent even with novice keyboard consumers. Anderson et al. quantifies the percentages for various keyboard such as chord, contoured split, Dvorak, and split fixed angle [13]. The authors strived to understand how physical, cognitive and perceptual learning occurs in various users. Even though alternative keyboards are beneficial in some aspects, productivity concerns hinder the efficiency factors and their acceptance greatly. The study conducted an experiment with sixteen subjects who were given multiple keyboards to type with. Their research claimed, "Learning percentage calculations revealed the percentage for the split fixed-angle keyboard (90.4%) to be significantly different ($p<.05$) from the learning percentages for the other three keyboards (chord, 77.3%; contour split, 76.9%; Dvorak, 79.1%). The average task completion time for the conventional QWERTY keyboard was 40 s, and the average times for the fifth trial on the chord, contoured split, Dvorak, and split fixed-angle keyboards were 346, 69, 181, and 42 s, respectively." The experiment concluded that the productivity of the split keyboard with QWERTY keypad is highest even though there might be some benefits to other keypad configurations.

2.3.2 Comfort

While several iterations of engineering design have been achieved since the release of the aforementioned ergonomic keyboard designed by McLoone and Hinckley, in order to quantitatively reduce the frequency of unnatural body mechanics, as well as, the amount of force required to operate the device, the topic of comfort remains subjective. Throughout ergonomic keyboard design literature, comfort is measured qualitatively by inquiring participants in experiments on how comfortable the proposed design is compared to a standard keyboard. This essential feedback helps confirm whether the mechanical improvement aligns with an end users psychological and physical approval.

2.3.3 Cost

Consumers of computer accessories are mindful of their purchases. Ergonomic keyboards are no exception as they cost more than traditional keyboards. Even with an appropriate build optimal for an end user manufacturing and logistical costs may very well end up being the barrier to a products success. At the same time, the build quality must not be sacrificed for a higher initial cost will be offset when compared to a cheaper keyboard will be undesired after one or two years of use [14].

2.3.4 Split and Slant Design Features

There have been several studies which have presented keyboards with a slant angle design reduce ulnar deviation [3,15,16,17,18]. The mitigation of ulnar deviation to a near neutral configuration causes a decrease of the carpal bones and carpal ligament on the tendons [19]. Such a reduction in the reaction force on the "tendons and their sheaths would decrease the risk of tenosynovitis in the wrist and finger flexor / extensor tendons" [3]. Neutral wrist ulnar deviation can be achieved when the split alternative keyboard has a slant angle of approximately 12.5° [3]. In a study where EMG data was collected on active keyboard users in 30 second intervals as they typed on standard and alternative keyboards with a slant, Strasser et al 20 confirmed a decrease in "EMG activity of the upper trapezius and anterior deltoid when using a keyboard with a fixed slant angle" [20]. From a usability perspective, Strasser et al found that the typing performance of alternative keyboards with a slant angle was only 5% less proficient in regards to typing speed and accuracy when compared to the performance of standard keyboards [20]. Overall, the slant angle received approval by users, as the time to adjust to the design was minimal and the adjustment of wrist orientation required little effort and was comfortable [21]. Split keyboards alone, in general, can be as effective as the introduction of a slant angle of 12.5° for the upper trapezius and anterior deltoid, but has no effect for wrist or forearm pronation [3].

2.3.5 Slope Design Feature

When placed on a horizontal surface, the average standard keyboard has a positive slope of 6 ° to 7 ° and the elevation legs are not extended. There is a near 10° difference in slope angle between a conventional QWERTY keyboard and the max optimal slope angle of an alternative keyboard. It is found that a negative "slope angle of 7.5° led to a near neutral wrist extension angle during typing" [3]. A neutral wrist orientation reduces the pressure amongst tendons and ligaments of the wrist [22]. The optimal range of keyboard slope angles for the majority of users is between 0° and –7.5° where the wrist extension angle is neutral and feedback on comfort is positive; any angle below that resulted in addition finger flexion [3]. From a productivity standpoint, mean typing speed and accuracy is consistent with a neutral to –7.5° [3]. Furthermore, participants in various studies regarded that a slope angle of –7.5° was as comfortable to use as a QWERTY keyboard [3,15,16].

2.3.6 Tilt Design Feature

There have been several studies which have presented keyboards with a tilt angle design reduces forearm pronation [3,15,16,17,18]. While studies suggest that the tilted angle of 30° effectively reduces forearm pronation by 20° to a resulting angle of 40°, the majority study participants described discomfort when interacting with this design; concluding this design feature was less comfortable than typing on a standard keyboard [15,16]. Despite this drawback, users with upper extremity pain or MSD's such as carpel tunnel syndrome (CTS), a common painful which results in numbness and tingling in the hand and arm, may be likely willing to overlook this feature as the benefits outweigh the obstacle. From a biomechanics point of view, when keyboards are tilted, wrist ulnar deviation is also reduced by 5° of radial deviation [3]. The elevated height resulting from tilting a keyboard to suggested levels require the horizontal surface that the keyboard is placed on to be lowered appropriately to maintain the posture of the forearms remains at a natural height [20].

2.3.7 Key Spacing

The International Organization for Standardization (ISO) evaluated previous literature which studied the biomechanical factors of key spacing as they pertain to productivity, comfort, and usability. The standard key spacing for the majority of computer keyboards, and recommended center-to-center horizontal and vertical key spacing is 19 ± 1 mm in length illustrated in Figure 5 [23].

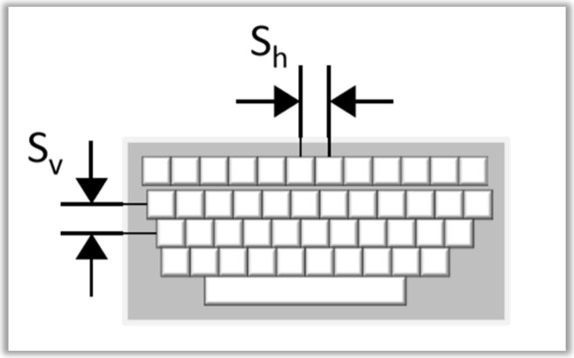


FIGURE 5: Horizontal (Sh) and vertical (Sv) key spacing on a conventional keyboard.

One study evaluated the association between key spacing and typing performance on a conventional keyboard with the key spacing length ranging from 15 mm to 19.7 mm [24].The experiment determined that typing performance remained constant for all key spacing except for when the spacing was set at 16.0 mm or less where participants with large fingers did not have favorable performance compared to a standard keyboard [24]. An illustration of key spacing is shown in Figure 6 which depicts virtual computer keyboards with square keys and various key spacing.

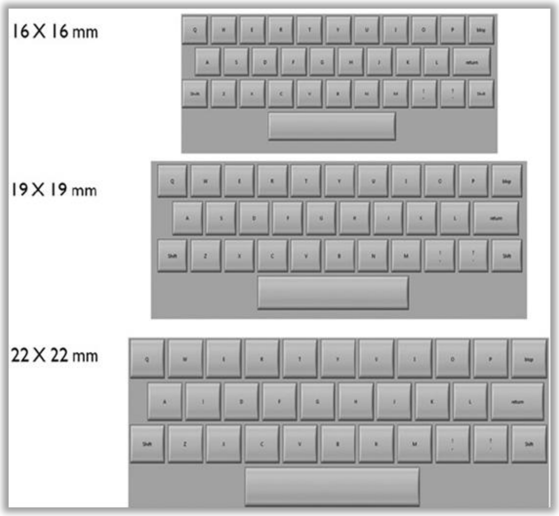


FIGURE 6: Virtual keyboards with square keys a height and width of 16, 19, and 22 mm. [26]. Across all keyboards, the spacing/ gutters between keys was fixed at 2 mm.

In “The Effect of Keyboard Key Spacing on Typing Speed, Error, Usability, and Biomechanics: Part 1” Pereira et al studied the relationship of key spacing on a conventional computer keyboard on forearm muscle activity and wrist posture. The results concurred with the aforementioned study where users who operated standard keyboards with 16 X 19 mm key spacing experienced unfavorable performance [23]. This study also reported that as horizontal key spacing was manipulated biomechanics were effected including: muscle activity in the forearms, wrist extension, and ulnar deviation. Their findings reported that the optimal key spacing length was between 17 and 19 mm.

2.3.8 Palm Support

Inclusion of palm rest reduces the frequency and impact in which the wrist of a user drops on a hard surface while typing and reduces contact pressure while the hand rests on it [4,15]. When used as a palm support, wrist rests results in a reduction in wrist extension and maintains blood flow. In addition, recent research has shown that a removable palm lift has the same benefits as a tilt keyboard and has been shown to reduce wrist extension more so than the tilt feature [4].

3. TRINITY DESIGN

The intent behind this proposed design, denoted as Trinity, is to encourage a neutral posture when typing, avoiding negatively impacting speed and accuracy, and eliminating the bulky appearance of the current alternative ergonomic keyboard products on the market.

3.1 Introduction to Trinity

It is inspired by a compilation of prescribed angles and dimensions mentioned in relevant literature. The adjustable split design aims accommodate a variety of individuals with an array of lengths and bulk of limbs, hands, and phalanges. Trinity leverages angle features described in relevant literature, as well as user feedback gathered from previous experiments. A condensed view of these insights is shown in Table 1.

Feature	Effects
Slant angle of 12.5°	• Places the wrist in near neutral position in the radial/ulnar plane
	• Minimal influence on wrist extension and forearm pronation
Separation distance equal to shoulder width	• Places the wrist in near neutral position in the radial/ulnar plane
	• Minimal influence on wrist extension and forearm pronation
Slope angle of -7.5° (wrist rest integrated into keyboard)	• Places the wrist in near neutral position in the flexion/extension plane
	• Increases wrist ulnar deviation by a few degrees
	• No apparent influence on forearm pronation
	• Reduces the electromyographic activity of the extensor carpi ulnaris slightly
Tilt angle of 20° to 30°	• Reduces forearm pronation to approximately 40° to 45 (from 60° to 65°)
	• Reduces ulnar deviation to near neutral
	• Minimal influence on wrist extension

TABLE 1: Synopsis of angles suggested by researchers based on a review of experimental data [3].

One of the main challenges for ergonomic keyboard design was to create an inclusive keyboard with both a split and tilting mechanism. In addition, after reviewing many keyboards in the market, none of them had both split mechanism as well as an attached number-pad. The proposed design, as illustrated in Figure 7, has both these features, which are favored heavily by users. The size of the keyboard is 465 mm x 152 mm with a 30 mm. The key size is designed to be 8 by 8 mm with the height of 4 mm (un-pressed). Key features of the keyboard design, the ergonomic impact of those features as they relate to reducing musculoskeletal disorders, and the expected proficiency in terms of learning curve, comfort, and productivity is explained in following paragraphs.

FIGURE 7: Top view of the proposed ergonomic keyboard, Trinity.

3.2 Slant Design and Numeric Pad

The basis of Trinity's split design of the keyboard was inspired from the suggested split angles of alternative keyboards. The contribution of this design is the aspect of splitting the keyboard in three parts as shown in Figure 8, and is the first ergonomic keyboard design to adopt this feature. The motive behind this approach is to account for the inclusion of a number pad. In the initial stages of design, the number pad was going to be a separate panel which was going to be either plugged in to the main body of the keyboard, or would be operated via Bluetooth technologies granting users flexibility to place the numeric pad in a convenient location for them. The latter option was omitted in order to avoid frustration from potential users due to too many customizable options in the set up. A separate numeric pad panel could result in further user experience frustrations. There is a possibility of the number pad falling down, an increase in clutter in individual workspaces, and also requiring excessive hand motions if used constantly resulting in potential repetitive strain injuries. The split mechanism is provided with adjustable supports which assists to keep the keyboard slant angles between 0° to 12.5° to reduce stress in the upper trapezius, anterior deltoid, as well as to position wrist ulnar deviation to a neutral alignment. This gull-winged position allows for a neutral ulnar deviation as fingers are place in a more natural position. Eventually, a curvature layout with the keys will be implemented to allow for shorter finger reach, reducing extension stress.

FIGURE 8: Trinity gull-wing position; the keyboard is split in three parts at favorable angles.

A power button is provided on the numeric pad module to not only provide power to the device, but to also conveniently wake the connected computer from sleep mode. This will allow users to return to their work station without having to perform excessive motion in order to turn their computers on. The keyboard is fixated with eco-mode which will turn off unnecessary functions and prevent excessive draining of battery from the connected computer or laptop. Finally, Trinity's numeric pad is provided in the middle similar to laptop with scroll wheel and customizable control drivers. It is LED lit for darker working environments. The keyboard is also facilitated with numeric operators (+,-, x, /) for mathematical work. For advanced mathematics, special keys can be set to perform trigonometry functions, integration, differentiation etc.

3.3 Special Keys

Special keys can be seen on the same key as F1 to F12 keys. They can be used by pressing the function button and one of the F1 to F12 keys simultaneously. To configure these keys, options and settings can be provided with keyboard driver software. These keys can be assigned functions such as open new file, google search, open mail etc. Even though there is no overwhelming demand from users for these special keys, the project design has tried to be all inclusive without much investment in the additional functions. This way the budget of the keyboard will stay in control and the users in need of these keys will be covered.

3.4 Palm Rest Pads

Rest pads were introduced to provide supports to palms of the hands and thereby reduce the stress for users who continuously use the keyboard for long time. Recent research suggests that wrist tension is reduced in such a manner that it is more effective that a tilt design giving the end user flexibility to select a configuration which is more comfortable and suitable to their needs.

3.5 Tilt and Slope Angle

A unique feature to Trinity is the dynamic ability to transition its orientation into various positions that is constrained to design angles (tilt, slope, and slant) that have been recommended by researcher to reduce musculoskeletal disorders. Users have a few options in regards to a slope angle: 0°, -7.5°, and 7.5°. At 0°, the keyboard is in its standard position as seen in Figure 7. From the standard position, there is an option to expand the kick standards that have been installed in the back of the frame as seen in Figure 9. When the stands closest to the user are extended, the keyboard has a negative slope of -7.5°. When the rear stands, located farthest from the user, are extended, the keyboard has a positive slope of 7.5°. These positive and negative slope angles have the same ergonomic benefits, they are options to give users the flexibility to select an orientation that is comfortable for them. These kick stands respond as a set, such that no individual stand will be extended on its own. The rear stands operate together, and the front stands also operate as a set unit. Finally, when both sets of stands are extended, the keyboard is raised. Being able to raise a keyboard may have an ergonomic benefit, if the user is operating the keyboard at a forearm height that does not place their forearms at a comfortable height while sitting.

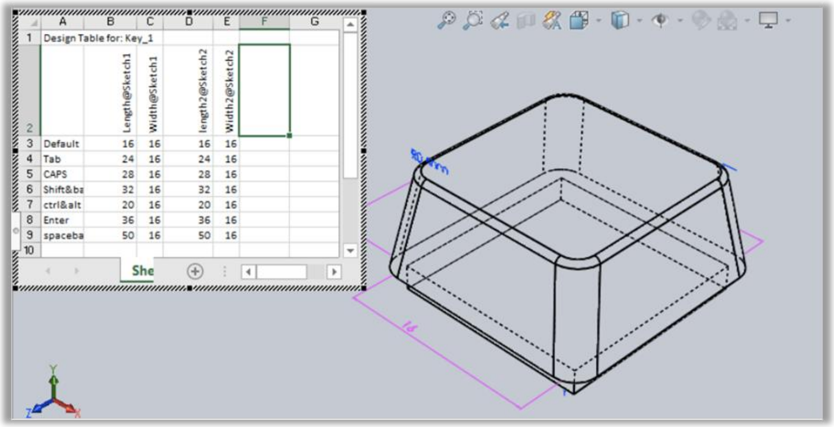
FIGURE 9: Trinity keyboard design in standard position. Dashed circles indicate the kickstand placement that is behind the base. The yellow circles represent rear stand set. The blue circles represent the front stand set closest to the user.

Trinity also has additional stands located towards the vertical center of each keyboard half as illustrated in Figure 10. When extended, the keyboard experiences to potential lock positions: a 20° tilt angle and a 25° tilt angle, which will reduce forearm pronation by 45° compared to a traditional QWERTY keyboard. These tilt angles were chosen opposed to 30° because user feedback from literature consisted of this being an uncomfortable orientation [3]. A tilt angle was included regardless of this feedback due to its proven ergonomic benefit of also reducing the need for ulnar deviation [3]. This tilt stand places Trinity in a 'tent' position. The stands operate in unison, such that not one side can be elevated at a time. Both standards are raised, lowered, and locked into place as a set. These orientations are intended to expand the expected user base to users to individuals experiencing musculoskeletal disorders or symptoms such as carpel tunnel syndrome, who require as many points of alleviation of tension, extension, and physical stress as possible. Eventually, the numeric pad will also be elevated to be in line with the peak height of each keyboard half to avoid a drop off.

FIGURE 10: Trinity keyboard design in the tented position displaying its tilting feature

3.6 Key Space

The default length of each key on Trinity is 16 x 16 mm with a 3 mm gap between keys resulting in a total 19 mm spacing. These dimensions have been shown to require minimal muscle activity and ensures proper wrist posture while maintaining a quality level of usability and productivity [23]. Dimensions of keys are shown on a table illustrated in Figure 11.



Design Table for: Key_1

	Length@Sketch1	Width@Sketch1	length2@Sketch2	Width2@Sketch2
Default	16	16	16	16
Tab	24	16	24	16
CAPS	28	16	28	16
Shift&ba	32	16	32	16
ctrl&alt	20	16	20	16
Enter	36	16	36	16
spaceba	50	16	50	16

FIGURE 11: Model of a Default Key.

The figure shows a model of a default key along with a table that has the dimensions of many of the keys on Trinity.

3.7 Voice Typing

For users with disabilities, Trinity leverages Microsoft accessibility technologies to. Even though most of the users do not need this facility, it is a customizable feature and can be chosen while ordering the keyboard. Users in the group can also leverage Microsoft accessibility functions provided within the Windows operating system.

3.8 Back-lit Keypad

It is a common useful trend to install back-lit keypads to the keyboard for working in darker environments or for highlighting the keys. Customizable back-lit LEDs are provided with the keyboard which will also perform the function of allowing keys to be easier to locate in dark environments, reducing eye strain. This also increases aesthetic appeal of the keyboard panel, as keyboards with back-lit keys are a popular feature based on consumer reports.

3.9 USB Ports

The number of USB ports provided with CPU or laptop are not enough due to advent of multiple accessory products supported by computers. This is the motivation to install at least 4 USB ports in total.

3.10 The Cost Benefit of Trinity

The cost related to repetitive strain injuries are incredible as well as the frequent occurrence of musculoskeletal symptoms. There are also costs that result from a decline in work productivity from employees who are suffering from MSD and symptoms. One survey reported that out of "1,283 computer users, 76 percent of males and 87 percent of females reported that they were experiencing at least one musculoskeletal symptom" [4]. Of the sample which experienced at least one musculoskeletal symptom, ~10 percent reported reduced productivity due to the pain from the musculoskeletal symptom. Other various quantifiable costs shown in Table 2 represent the value of a single repetitive strain injury.

Cost	Description	Source
$159.20 per day	Average white-collar labor rate	BLS 2000
12 days	Average number of lost work-days per RSI injury	BLS 2000
$38,500	Average workers' compensation upper extremity RSI claim	CA CHSWC, 2000
16.8 hours	Average loss of productivity per month	Hagberg et al [8]

TABLE 2: Sample of Quantitative Labor and Medical Costs Associated with RSI [4].

Based on studies done by the BLS, the average total medical and labor replacement costs of a single repetitive strain injury is ~$40,000 [4]. Therefore, there is a significant financial incentive for reducing risk factors for repetitive strain injuries. In "Reducing the Incidence and Cost of Work-related Musculoskeletal Disorders with Ergonomic Input Devices" it was determined that a 10 percent reduction in injuries and symptoms could yield a significant upper six figure reduction in costs per year [4]. As mentioned in the introduction of this paper, to avoid these high costs, it is recommended to address symptoms early through ergonomic interventions in the workplace. Trinity has the capability to avoid the occurrence of numerous musculoskeletal symptoms. Therefore, if the consumer sales price is much greater than the price of a standard keyboard, as expected for an ergonomic keyboard, the long term ergonomic benefits will outweigh upfront financial costs.

3.11 Comparative Analysis

In order to assess the advantages of the Trinity Keyboard, it has to be compared to one of the most widely known, adopted, backed by heavy research, and number one selling ergonomic keyboard that has been designed and manufactured by Microsoft [4]. The latest innovations in ergonomic design, including design features mentioned in this work has be the Sculpt Ergonomic Keyboard with the Natural keyboard layout as seen in Figure 12 [4]. Key features include its curved key frame reduces the amount of force required for users to press each key, while the arc takes into account the various lengths of fingers, reducing the reach required to successfully interact with distant keys by forcing the keys closer to the center of the hand.

FIGURE 12: A top view of the Microsoft Sculpt Ergonomic Keyboard.

While there are clear advantages to this fixed alternative design including its mass appeal for general and novice users due to easy set up and no customizable features, this one size fits all approach is not effective for niche users with uncommon limbs, hands, and phalanges [4]. The biggest difference is that the Trinity design can be set up in various ways to accommodate any user. It has a unique design with both a split and tilting mechanisms which creates a more inclusive keyboard than the Microsoft Sculpt Ergonomic Keyboard. Moreover, The Trinity design has a split mechanism which makes it able to adjust the slant angles between 0° to 12.5°. On the other hand, the Microsoft Sculpt Ergonomic Keyboard has a fixed 6° design which allows for more of a natural use due to the similarities it has with the straight keyboard that is commonly used. Research indicates that having a full split design with 12° angle would improve the wrist posture [27]. Additionally, the Trinity design has an attached number-pad while the Microsoft Sculpt Ergonomic Keyboard does not which can be frustrating to some users.

3.12 Summary of the Ergonomic Benefits of the Trinity Keyboard Design

Trinity's design accomplishes key objectives of a successful ergonomic keyboard design. First, Trinity achieves the goal of reducing musculoskeletal disorder symptoms. With its slant angle in both the gull-wing and tented positions place wrists in a proximate neutral position in the ulnar and ulnar plane. The split design separates the keyboard in halves such that the center of each half is equal to average shoulder width. This also places wrists in a near neutral position in the radial and ulnar plane. The slope angles place wrists in a near neutral position in the flexion and extension planes, and reduces electromyography (EMG) activity of the extensor carpi ulnaris. Finally, the tilt angle and palm wrest (wrist pad) reduces forearm pronation by 10-15° when compared to a standard keyboard, as well as ulnar deviation to a neutral position. Second, Trinity achieves the goal of maintaining a comfortable and productive user experience which ideally would not take much time for new users to adapt to. Each position was considered favorable from the aspect of comfort based on user feedback from all aforementioned research in the literature review of this paper except for the tilt angle feature. As discussed, the tilt optional feature was included in the Trinity design to alleviate pain suffered from individuals with musculoskeletal disorders. Each configuration that Trinity has is expected to result in a user experience that is either as productive as a standard keyboard, or maybe slightly less productive compared to a standard keyboard with the trade-off being alleviation of musculoskeletal symptoms.

3.13 Trinity Design Criticism

Trinity's multiple positions are its most unique aspect, while at the same time its greatest concern. Offering users too many customizable options can lead to an overwhelming and frustrating experience. To address this, each orientation that Trinity offers is mechanically fixated such that a combination of positions is not possible since each keyboard half transition operates in unison (i.e. the right half of the keyboard can only be adjusted to have a slant angle if the left half is adjusted to that same angle with the same plane.) This attempts to limit the number of choices to a user. Trinity also offers its standard position to users who do not desire any customization, but still want to experience the health benefits of an ergonomic keyboard. Another aspect of Trinity's design is the linear layout of the keys. Modern ergonomic keyboard design have a curved array which reduces extension of fingers to reach keys. This feature would be introduced in a future iteration. Finally, the numeric pad requires the ability to be raised when Trinity is in its tent position to give the structure a seamless curved form for usability purposes.

4. CONCLUSION

The rate of occurrence for repetitive strain injury symptoms for white-collar computer users is tremendous. Along with medical compensation costs, there are also costs that result from a decline in work productivity from employees who are suffering from MSD and symptoms. Addressing repetitive strain injury symptoms before they become injuries is crucial because prevention is not only easier to manage, but it is also financially advantageous than treating them. There have been numerous research efforts in designing an ergonomic keyboard which reduces musculoskeletal symptoms based on various angles and dimensions. These designs also strive to maintain user productivity as compared to standard computer keyboards, while at the same time keeping a level of comfort to ensure user adoption. By incorporating Trinity, a user-centric ergonomic keyboard which encompasses aforementioned design features and user feedback, with an integrated ergonomics program in the office can improve employee health and reduce business costs by effectively mitigating the instance of repetitive strain injuries.

4.1 Future Work

Most immediate, there are design improvements that are under consideration as mentioned in this paper. More improvements will be considered as Trinity goes under user testing and feedback is gathered. Aside from mechanical design, an experimental design and survey will be conducted to extract insights from users for improvement, as well as to confirm assumptions regarding musculoskeletal symptom reduction. This would require a physical working prototype be developed of Trinity to compare with a standard computer keyboard. Finally, during the experimental design, Trinity would be compared with the Microsoft Sculpt to obtain a greater understanding of the pros and cons between a fixed and adjustable ergonomic keyboard design.

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