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Article

Kinematic Analysis of the Forward Head Posture Associated with Smartphone Use

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Abstract: Background: Frequent use of mobile devices has a known association with musculoskeletal neck pain. This study sought out to localize the region with greatest flexion in the cervical spine and explored the role of symmetry in maintaining the pose during texting. Methods: Three inertial measuring units (IMUs) superficially attached along the cervical spine divided the cervical spine into two measurable segments. Twenty-five subjects participated in the study and performed three tasks when using smartphones: sitting, standing, and walking. Data from each IMU were used to calculate the flexion of cervical divided into two segments: craniocervical junction (C0–C1) and subaxial (C1–C7). Results: The greatest flexion by far occurred at C0–C1. While sitting, standing, and walking, the mean flexion angles were $33.33 \pm 13.56°$, $27.50 \pm 14.05°$, and $32.03 \pm 10.03°$ for the C0–C1 joint and $-3.30 \pm 10.10°$, $2.50 \pm 9.99°$, and $-1.05 \pm 11.88°$ for the C2–C7 segment, respectively. There is a noticeable pattern of yaw movement of the head, with a slow rotation toward symmetry and a fast corrective movement toward the smartphone held in one hand. Conclusions: This study identified the region of greatest contribution toward forward flexion along the cervical parameters during various tasks involving smartphone use. With each task, the greatest contributor to head flexion was the C0–C1 joint. There is involuntary rotation of the cervical spine toward symmetry when texting.

Keywords: spine; motion analysis; wearable sensors; biomechanics; smartphone

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1. Introduction

Musculoskeletal disorders (MSDs) are the leading cause of work absenteeism and loss of productivity across the member states of the European Union [1]. Work-related MSDs comprise a large proportion of that category. The most commonly reported biomechanical risk factors include, among others, undue repetitions and awkward postures [2]. In the past several years, numerous studies have reported a positive correlation between musculoskeletal pain and smartphone use [3–7]. The current daily usage of handheld devices by adolescents is estimated to be 5–7 h [8], which has led to a growing concern about the screen time's impact on the stress applied to the neck and cervical spine. While children and adolescents are significant users of handheld devices, they lack awareness of the potential long-term dangers of poor posture. Recent clinical research has shown that children and adolescents with persistent musculoskeletal pain are at risk of chronic pain in adulthood [9–11]. With neck pain ranked as the 8th health condition for most years lived with disability in 15- to 19-year-olds, neck pain surpasses any other well-known adolescent health problem such as substance abuse, road accidents, and asthma [12]. A relatively new condition called text neck syndrome refers to the onset of cervical spine degeneration due to the long-term use of mobile devices with poor posture [13]. Clinical symptoms of text neck syndrome range from musculoskeletal pain to neurological damage affecting the eyes, lungs, and heart. Despite the syndrome's symptoms, the mechanism of cervical degeneration has not been proven, and only a few studies have identified its significant correlation with smartphone use [14,15].

This study aims to identify the cervical spine region with the maximum flexion during smartphone use by using 9-axis inertial measuring units (IMUs). In addition, we looked at the head and neck symmetry, which may play a role in developing the neck–shoulder pain, as suggested in an article by Xie et al. [16]. This was accomplished by analyzing the head rotation over time (ϒ—Figure 1) during the use of a smartphone. The findings from this study can provide a more precise biomechanical understanding of the effect of smartphone use on the cervical spine, which is essential for future studies investigating the stress experienced by the neck's components, emphasizing the cervical spine's symmetry.

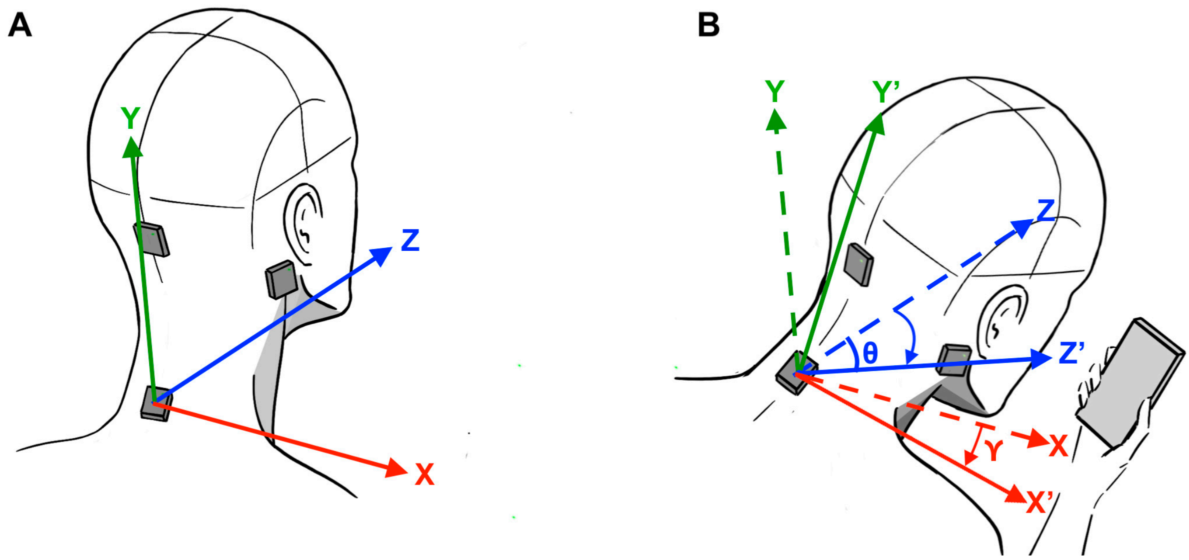

Figure 1. Euler vectors used in measurements. (**A**) neutral position, (**B**) posture during smartphone use. Θ—head/neck flexion; ϒ—head/neck rotation.

2. Materials and Methods

2.1. Inclusion Criteria

This study included 25 subjects (11 women and 15 men) from the Medical University of Gdansk. There were 21 medical students and 4 neurosurgical residents. The mean age was 23.36 (SD 2.79). The subjects selected to participate in the study had to have no history of spine disease or spinal injury, or have undergone spinal surgery. Issues must also have no ongoing spinal pain, neurological defects, or symptoms showing a pathological process in the spine. All requirements were carefully read, and written consent was given by each participant prior to the measurements. The study was approved by the local ethics committee at the Medical University of Gdansk (NKBBN/145/2021) and complied with the Declaration of Helsinki.

2.2. Apparatus and Sensor Attachment Points

The MetaMotionR (MMR—MbientLab, San Francisco, CA, USA), a 9-axis IMU, was used in this study. This unit consisted of a 6-axis accelerometer + gyroscope and a 3-axis magnetometer for a real-time 9-axis sensor fusion. Using the MMR and a mobile application receiving the IMU data has been previously proven to be reliable in measuring spine flexion/extension [14,17]. To calibrate the measurements, Physics Toolbox Sensor Suite Pro application version 1.9.1 (MbientLab) was installed on the observer's smartphone and connected with tcorrehe IMUs via Bluetooth (Figure 2). The sampling frequency in the application was set to 100 Hz. A total of 4 IMUs were used, each firmly attached with tape over one of the following 4 locations: the skin overlying the external occipital protuberance, below the right mastoid process, just below the C7 spinous process, and the posterior aspect of the participant's smartphone. The 3 IMUs superficially attached to the patient allowed flexion analysis of the spine to be divided into three parts: the atlanto-occipital joint (C0–C1), C2–C7 vertebral levels, and torso. The IMU was also attached to the smartphone to calculate the screen's absolute inclination.

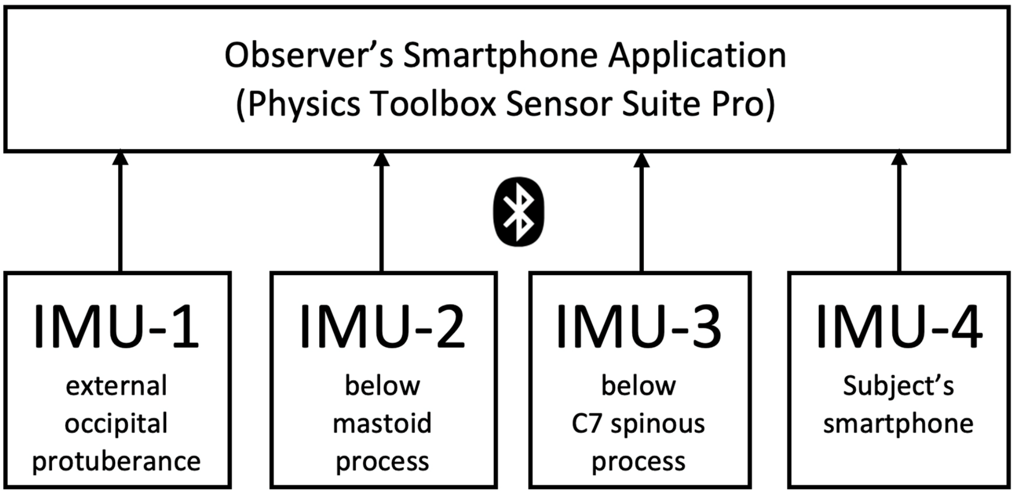

Figure 2. Sensor setup.

2.3. Tasks and Measurements

Patients were analyzed in three postures: sitting, standing, and walking. Four measurements were taken. The first measurement (M1) was a calibration phase that measured the subjects seated in a chair without their legs crossed and looking straight forward for 5 min. M1 was a neutral zero position as it required minimal energy expenditure, and it is when the head, neck, and torso are aligned with the rest of the spine. The data from the IMUs during M1 were implemented into all the following measurements as the reference coordinate.

The second measurement (M2) required the subjects to text on the smartphone with one hand, measured for 5 min. When the subjects were asked to perform M2, the forward flexion angles produced by C0–C1, C2–C7 vertebral levels, and torso were evaluated with respect to the one stored in the calibration phase from M1. The third measurement (M3) required the subjects to stand for 15 s while using their smartphone in one hand. The fourth measurement (M4) required the subject to walk 10 m at their own pace while texting with one hand. As explained, the forward flexion vectors would be evaluated with respect to the one from the calibration phase (M1). M2, M3, and M4, which involved smartphone use, required the subjects to always maintain eye contact with their phone. During all 4 measurements, the subjects were advised not to speak or make any unasked movements. Subjects were allowed to use their smartphones throughout the duration of M2, M3, and M4.

2.4. Segment Angle Calculation

Data from each IMU were used to calculate the flexion of cervical divided into two segments: craniocervical junction (C0–C1) and subaxial (C2–C7). Due to the limited movement of the thoracic spine, the torso was used as the base reference. The IMU attached at the C7 spinous process (IMU-3) provides the data on torso flexion, expressed as the absolute angle obtained from the calibrated Euler vector. Similar studies analyzing movement in this region have also used a single IMU, and attaching the device to the chest or upper back is all shown to be effective [18–20]. The IMU attached below the mastoid process (IMU-2) was treated as the uppermost point of the C2–C7 vertebral levels (approximately at the C1 vertebral level). Its placement simultaneously is unaffected by head flexion. Data from the IMU-2 and IMU-3 were used to measure the flexion of the C2–C7 vertebral levels and were calculated by the following formula:

$$\boldsymbol{\theta}_{\mathbf{C2-C7\ vertebral\ levels}} = (\boldsymbol{\beta} - \boldsymbol{\alpha})$$

where $\boldsymbol{\theta}_{subaxial}$ is the degree of the flexion of the C2–C7 vertebral levels, $\boldsymbol{\beta}$ is the change in pitch detected by IMU-2, and $\boldsymbol{\alpha}$ is the change in pitch detected by IMU-3. The data from the IMU attached to the external occipital protuberance (IMU-1) along with IMU-2 were used to calculate the C0–C1 joint flexion.

By subtracting the pitch detected by γ (IMU-1) from $\boldsymbol{\beta}$, $\boldsymbol{\theta}_{head}$ (flexion of the C0–C1 joint) was provided.

$$\boldsymbol{\theta}_{head} = (\gamma - \boldsymbol{\beta})$$

2.5. Symmetry Analysis

For symmetry analysis, the yaw value was used (ϒ—Figure 1). The use of data merge from multiple sensors within each IMU provided the absolute azimuth (heading) for each device. This value was recorded per IMU during the M1 (calibration—a neutral value) and M2 tasks. The resulting head yaw was calculated by subtracting the heading of IMU-1 from the respective value of IMU-3.

3. Results

The C0–C1 joint was the largest contributor in forward flexion out of the two segments analyzed from the cervical parameters. When analyzing the mean flexion angles during sitting and walking, the C0–C1 joint was the only contributor to flexion among the cervical parameters as only extension (indicated by a positive value in Figure 3) was measured at the C2–C7 vertebral levels. During sitting, an average change in –33.33 ± 13.56° was measured by the C0–C1 joint, and an average change in 3.30 ± 10.10° was measured by the C2–C7 vertebral levels. During standing, an average change in –27.50 ± 14.05° was measured by the C0–C1 joint and an average change in –2.50 ± 9.99° by the C2–C7 vertebral levels. During walking, an average change in –32.03 ± 18.35° was measured at the C0–C1 joint and an average change in 3.30 ± 10.10° at the C2–C7 vertebral levels. The mean flexion of the overall cervical parameters was similar with all tasks: during walking, which was approximately 5.82° greater than standing ($p < 0.05$) and approximately 2.76° greater than sitting.

Comparing the flexion angles for each task, statistically significant differences were present when comparing the angle of the C0–C1 joint to the C2–C7 vertebral levels and the torso ($p < 0.0001$). Additionally, one-way ANOVA confirmed a significant difference in the position of the smartphone during each of the three tasks ($p < 0.005$). Despite changes in the position of the smartphone during each measurement, the head position remained balanced. On the other hand, the flexion of the C0–C1 joint was far greater than that of the C2–C7 vertebral levels and torso in each task performed ($p < 0.001$).

With regard to the symmetry, a distinctive pattern of head movement was noted in 20 out of 25 subjects during the M2 task. Namely, there was a sawtooth yaw movement over the course of the measurement period, with noticeable slow and fast phases (Figure 4). The slow phase was counterclockwise (left) in all except one subject. The mean amplitude of oscillations was 19.77° (range 15.58–28.13); the mean frequency was 12.57 mHz (range 4.03–35.44). The correlation of frequency with the amount of neck flexion as evaluated with the Spearman coefficient was statistically significant at $p < 0.001$. There was no correlation between the amplitude and neck flexion. For the control M1 task, only low-amplitude random fluctuations were noted (Figure 4).

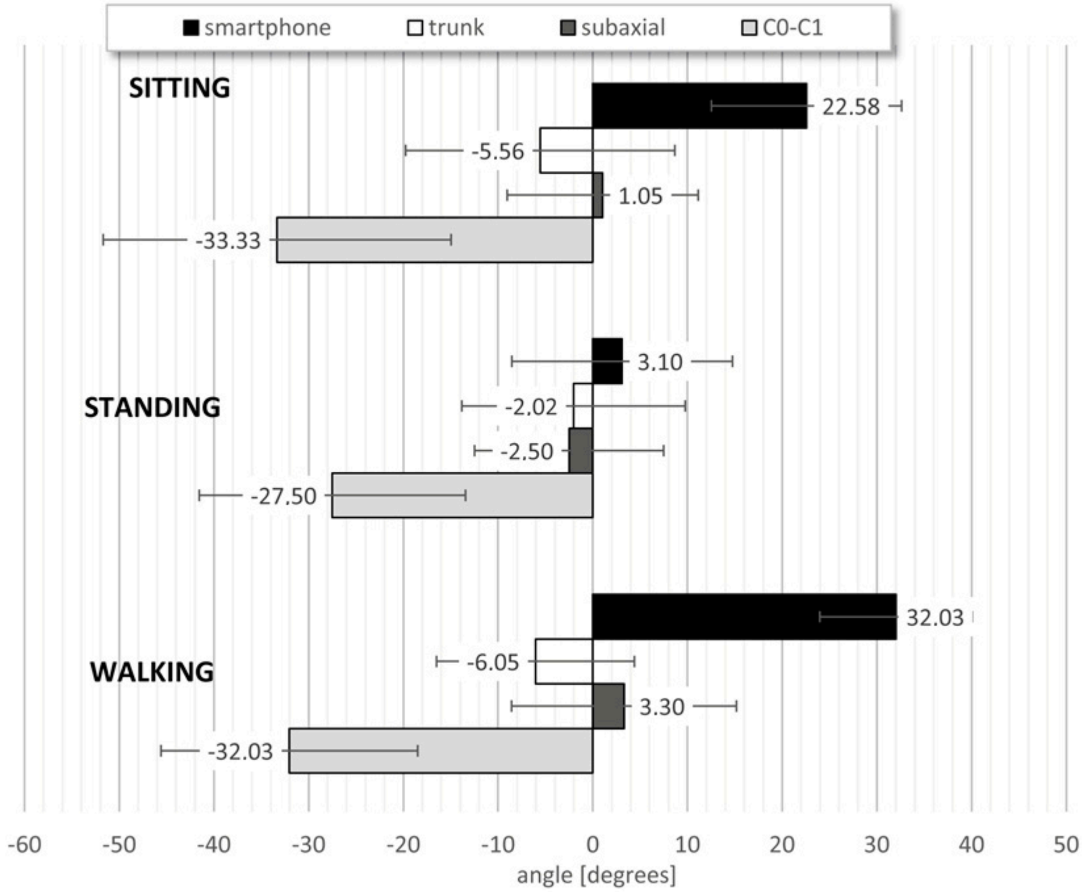

Figure 3. Changes in flexion at three segments of the spine and inclination of smartphone screen during three tasks.

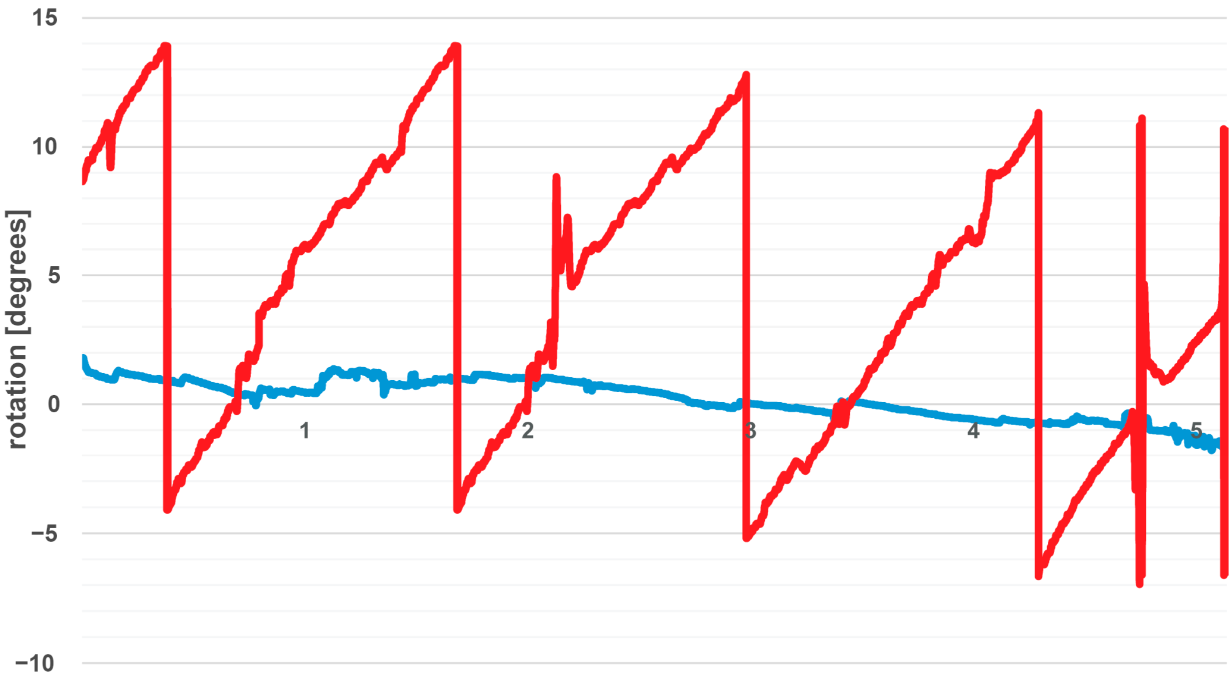

Figure 4. Raw data of head rotation during 5 min of texting (red line) and in neutral pose recorded for 5 min (blue line).

4. Discussion

The term "text neck" describes a repetitive stress injury caused by the prone posture associated with the overuse of smartphones for prolonged periods [21]. It has been shown that it leads to accelerated degeneration of the cervical spine in children and adolescents [7]. An inadequate posture equally affects all components of the cervical spine: intervertebral discs [14], uncovertebral joints [22], and ligaments [23]. An often-quoted hypothesis is based on the observation that the neck flexes forward during smartphone use, with the fulcrum of movement in adult at the C5/6 level [24].

This study was designed to look into the biomechanics of text neck syndrome, emphasizing the role of craniocervical junctions vs. subaxial levels. It identified the C0–C1 joint as the major contributor in forward flexion during smartphone use during sitting, standing, and walking. The C2–C7 vertebral levels remained almost stationary. The main compensatory movement to counter the center of gravity shift caused by the significant flexion angle at the C0–C1 joint was at the torso level.

This study's findings also question a reference heavily cited when supporting theories on the negative long-term effect of smartphone use on the cervical spine and text neck syndrome. A frequently referenced study by Hansraj et al. [8] calculated the combined force exerted onto the neck's muscles, ligaments, and tendons at various flexion angles. The study incorporated realistic values of the head and neck into a simulation program while using the C7 vertebra as the lowest point of measurement. At neutral position when no flexion was present, the estimated weight experienced by the neck was 5 kg [8]. At 30° flexion, the force drastically increased to 18 kg, 22 kg at 45°, and 27 kg at 60°. Although the simulated results using the values inputted are likely to be accurate, the findings from our study suggest that many of the forces reported by Hansraj et al. are most likely not caused by the altered natural posture of the spine but rather the result of the shift in gravity point. Due to the C0–C1 joint being the most superior flexional point in the human body and simultaneously contributing to nearly the entire flexion movement, the flexion angle when measuring from the C7 vertebra is unlikely to be extreme. The findings from a recent study by Kim et al. would support this theory as the study assessed lumbar, thoracic, and cervical flexion during smartphone use while sitting and standing [25]. While treating the cervical parameters as a single joint segment, the mean cervical flexion while sitting was measured to be only 22.06° and 28.25° while standing. Given that the mean flexion angles identified by Kim et al. and our study range only around 20°–30° when performing the common tasks involving smartphone use, we encourage readers when interpreting the findings from Hansraj et al. to bear in mind that the extreme angles reported such as 45° and 60° are most likely not experienced by an average individual.

This study was largely inspired by the concept of the cone of economy introduced by Dubousset in 1994 [26]. The cone of economy (CoE) refers to a cone-like region beginning at the feet and extending upward surrounding an individual. It was originally created to assess patients with spinal deformity at the lumbopelvic region. The ability for an individual to remain inside the cone is vital in the long term to keep energy expenditure at a minimum by allowing the line of gravity to fall within the base of support [27,28]. Spine disorders or poor posture, in general, displaces the line of gravity outside the base of the cone and thus requires excessive muscle training [29]. Prolonged posture identified outside the cone will result in muscular pain and a possible alteration of the biomechanical property of the spine. In theory, it is feasible to create a "safety envelope" for neck displacement parameters encountered during prolonged postural strain, as with the text neck. Such set of rules has already been proposed as neck injury criteria by The National Highway Transportation Safety Administration (NHTSA) called the N_{ij} [30]. It was introduced as a part of a comprehensive crash protection safety standard used in the assessment of advanced automotive restraint systems [31].

The cervical kyphosis thought to be observed during smartphone use can be hypothesized to potentially displace the gravity line outside the ideal region. However, from our findings, the head flexion observed is almost entirely based on the C0–C1 rotation. Despite the extensor muscles of the neck being largely targeted, which is most likely the cause of the reported musculoskeletal pain, the head's center of gravity is located near the sella turcica [32]. Therefore, the sagittal profile of the cervical spine would remain unaffected and, arguably, would not contribute to the degeneration of the cervical spine. Our results do not negate the detrimental effect of smartphone use on the health of the C2–C7 vertebral levels. They merely show that, if present, it is rather secondary to the posterior tension band wear and tear.

Another factor that may play an important role in developing neck and arm pain related to smartphone use is the posture symmetry. It has been shown that smartphone users who perform texting with one hand ("unilateral texting") are more likely to develop neck–shoulder pain than those who use both hands ("bilateral texting") [16,33]. In this study, subjects were performing unilateral texting. Our study's secondary goal was assessing the role of head rotation in developing pain. Initial analysis failed to demonstrate any relationship; however, with the extended recording of the head position, a sawtooth pattern became apparent. One plausible explanation of this finding is that the slow phase represents an involuntary head movement toward a more favorable symmetrical configuration. Without a doubt, periodic head oscillations require additional muscle work, and they not only consume additional energy but also may contribute to the neck pain.

In recent years, the technology behind IMU sensors greatly improved. Among the advances, the incorporation of the sensor fusion technology at a reasonable price was a breakthrough as it allowed for a precise measurement of the absolute angular position in any given plane. Their miniaturization and capable wireless data transfer have resulted in their use in many recent biomechanical studies, including several spine-related studies [19,34–37].

5. Study Limitations

This study was conducted in an experimental environment to reduce the possibility of confounding variables. Despite the tasks performed by the subjects being derived from every-day behaviors, the subjects may have differently performed in their natural setting when not under any observation. Additionally, we assumed the postural stability of the thoracic spine to be maintained during all tasks given its ridged anatomical structure. Therefore, it is safe to assume that no significant flexion or extension by the thoracic spine was present during the sitting and standing phase, which could affect our data. However, regarding walking, it is less obvious and requires a validation study on the matter. Therefore, our results regarding the walking phase should be interpreted with caution. The data obtained from the sitting position may also be less reliable. We understand that the chair used by an individual will heavily determine the spine flexion angles. Therefore, individuals among a population that use non-ergonomic chairs, especially those without back support, would not apply to the findings of this study. It is also important to mention that the IMU attachment points are all superficial, and, therefore, their data monitoring of the bony landmarks is not exactly accurate. However, multiple recent studies have assessed this limitation with IMUs by comparing with conventional methods for joint movement analysis (commonly with the Vicon Motion Capture System) and confirmed that performance differences were not significant [17,35,38]. Last but not least, the present study would benefit from surface EMG recording, especially with regard to an increased work exerted by neck muscles during head oscillations.

6. Conclusions

This study identified the region of greatest contribution toward forward flexion along the cervical parameters during various tasks involving smartphone use. Though the value in the degrees of flexion of the C0–C1 joint and C2–C7 vertebral levels did not greatly differ between the different tasks performed by the subjects, the differences were still significant. On the other hand, the tilt angle of the smartphone significantly varied during each of the three tasks. With unilateral texting, the head slowly rotates toward symmetric configuration with corrective fast phase. The correlation between the frequency and amount of neck flexion as evaluated with the Spearman coefficient was statistically significant. Future studies should focus on how this pattern affects the cervical spine's complex biomechanics. To strengthen the overall findings of this study, we encourage studies to test other common movements and tasks that were not covered. By improving the generalizability and consistency of the current findings on the biomechanics behind smartphone use, the steps in reaching public awareness on the potential long-term hazards of poor posture are heading toward the right direction.

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