“Far” and “Near” Visual Acuity While Walking and the Collective Contributions of Non-Ocular Mechanisms to Gaze Stabilization

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Abstract

Gaze stabilization was quantified in subjects (n=11) as they walked on a motorized treadmill (1.8 m/s) and viewed visual targets at two viewing distances. A "far" target was positioned at 4 m (FAR) in front of the subject and the "near" target was placed at a distance of 0.5 m (NEAR). A direct measure of visual acuity was used to assess the overall effectiveness of the gaze stabilization system. The contributions of non-ocular mechanisms to the gaze goal were also quantified using a measure of the distance between the subject and point in space where fixation of the visual target would require the least eye movement amplitude (i.e. the head fixation distance (HFD)). Kinematic variables mirrored those of previous investigations with the vertical trunk translation and head pitch signals, and the lateral translation and head yaw signals maintaining what appear as anti-phase relationships. However, an investigation of the temporal relationships between the maxima and minima of the vertical translation and head pitch signals show that while the maximum in vertical translation occurs at the point of the minimum head pitch signal, the inverse is not true. The maximum in the head pitch signal lags the vertical translation minimum by an average of greater than 12 percent of the step cycle time. Three HFD measures, one each for data in the sagittal and transverse planes, and one that combined the movements from both planes, all revealed changes between the FAR and NEAR target viewing conditions. This reorganization of the non-ocular degrees of freedom while walking was consistent with a strategy to reduce the magnitude of the eye movements required when viewing the NEAR target. Despite this reorganization, acuity measures show that image stabilization is not occurring while walking and viewing the NEAR target. Group means indicate that visual acuity is not affected while walking in the FAR condition, but a decrement of 0.15 logMAR (i.e. 1.5 eye chart lines) exists between the standing and walking acuity measures when viewing the NEAR target.

Introduction

From a gaze control perspective, walking is far more complex than a simple forward translation of the body. Vertical and lateral translations are also a part of the movement and rotations of the body and head are present as well. The nature of these movements, primarily those in the sagittal plane, has been the focus of prior investigations. Disparate results regarding the magnitude of these movements exist (Pozzo et al. 1990; Pozzo et al. 1991; Bloomberg et al. 1992; Hirasaki et al. 1993; Berthoz and Pozzo 1994; Bloomberg et al. 1997; Hirasaki et al. 1999; Moore et al. 1999). Reported values for the magnitude of vertical translation vary between ~2 to 9 cm and head pitch amplitudes range from 1.5° to 8.5°. Less emphasis has been placed on the movements in the transverse plane, but similar variation exists. Inter-subject differences account for some of the variation. Moore et al. (1999) showed differences in predominant frequency of the vertical translation waveform based on subject height. Different experimental paradigms can also account for some of the variation. Walking velocity (Hirasaki et al. 1999), visual target distance (Bloomberg et al. 1992; Moore et al. 1999), and the actual visual fixation task (Mulavara and Bloomberg 2002) have all been shown to affect the magnitudes of individual waveforms.

Although magnitude differences are common, reports on the coordinative relationships between waveforms show consistency. It has been well established that as the body translates down, the head rotates up, and vice versa. A similar relationship exists for lateral translation of the body and head yaw (Moore et al. 2001). Translations of the body to the right are accompanied by head rotations to the left, and vice versa. Based on the relationship in the sagittal plane, Pozzo et al. (1990) theorized that the collective action of the vertical translation and head pitch was such that the naso-occipital axis of the head throughout the step cycle intersected at a fixed point in space. Other authors have used this concept of the head fixation point as a way to quantify the interaction between the trunk translation and head pitch during locomotion. Hirasaki et al. (1999) calculated the head fixation point using the extremes of the head pitch and vertical translation waveforms and reported it in subject-relative terms by measuring the distance between it and the subject. They showed that this head fixation distance (HFD) in the sagittal plane was consistent within a subject for walking velocities above 1.4 m/s. Moore et al. (1999) expanded the idea further using a statistical methodology for calculating HFD using data from throughout the stride cycle.

Using an experimental paradigm that required visual fixation of targets placed at distances between 0.25 and 2.0 m, the Moore et al. investigation showed that HFD could be influenced by viewing distance and that accompanying eye movements were dependent upon the relationship between the HFD and the viewing distance of the visual target. This latter point is understandable when it is considered that a visual target placed at the head fixation point would theoretically allow the eyes to remain fixed relative to the head without compromising visual fixation on the target. It follows then that a change in the HFD measure that brings the head fixation point closer to the visual target location would therefore result in reducing the eye amplitudes required to achieve visual fixation. Because the calculation of HFD is a composite variable created from head pitch and vertical translation, a modification in either of these signals can affect the HFD value. Therefore HFD may be better than independent measures of individual movement parameters at assessing whether non-ocular mechanisms are contributing to the gaze stabilization goal.

Similarly, a variable that combines the collective contributions of both ocular and non-ocular gaze control mechanisms is likely the best variable for assessing the overall ability of the gaze stabilization system to maintain gaze fixation while walking. A measure of visual acuity could serve in this capacity. Measures of acuity during subject movement have been used for ergonomic evaluations (Boff and Lincoln 1988; Griffin 1990), vestibular research investigations (Demer and Amjadi 1993; Tian et al. 2001) and clinical diagnostics (Herdman et al. 1998; Schubert et al. 2001). Each provided valuable information, but direct measures of acuity while walking are limited. Acuity during locomotion has been inferred through calculations of gaze (Crane and Demer 1997; Moore et al. 1999), but these measures can be subject to measurement error. Hillman et al. (1999) compared the performances on a number reading task between vestibular deficient patients and a group of control subjects while walking. The same paradigm was used to evaluate the effects of spaceflight on dynamic visual acuity (DVA) (Bloomberg and Mulavara 2003). More recently, pilot data for the current investigation was published showing the feasibility of using a new set of evaluation tools for assessing acuity while walking (Peters and Bloomberg 2005).

The purpose of this investigation was to test whether the changes in non-ocular body movements that accompany changes in visual target viewing distance effectively assist in the gaze stabilization goal. Variables throughout the body have been shown to be affected by the gaze fixation goal performed while walking (Mulavara and Bloomberg 2002). Through a measure of the head's point-of-regard during walking the collective contributions of these non-ocular contributors to the gaze stabilization goal can be quantified. These contributions can be observed within a single movement plane as has been done previously, but a new measure (3dHFD) that simultaneously incorporates measures from the sagittal and transverse planes can also be calculated. In addition, direct measures of visual acuity while walking will be used to assess the overall effectiveness of both the ocular and non-ocular gaze stabilization mechanisms. These measures will be repeated using two visual-target viewing distances to determine whether non-ocular mechanisms are being reorganized to assist in the gaze control task and to assess whether any changes are successfully employed to maintain a consistent acuity for each target distance.

Methods

Subjects

Twelve subjects provided written informed consent to participate in this experiment. Data from one of the subjects was later omitted from the analysis because of hardware problems. Of the remaining subjects, there were four males and seven females. Their ages ranged from 22 to 39 years (mean 29.9 years). The study protocol was approved by the Institutional Review Board at Johnson Space Center prior to the start of data collection and each subject's fitness to participate in the study was evaluated using a modified Air Force Class III physical.

Protocol

During a single data collection session for each subject, data were collected while four visual acuity assessments were made. The first required the subject to stand in the center of a non-moving treadmill belt and verbally identify the orientation of the gap in Landolt Ring optotypes. The optotypes were displayed sequentially on the screen of a laptop computer that was centrally placed at a distance that was 4 meters (FAR target) from the center of the treadmill belt. The height of the laptop screen was adjusted to eye height prior to the subject getting on the treadmill. While on the treadmill, the center of the laptop screen was approximately 3° below the subject's eye level. The second acuity assessment was made while the subject walked on the treadmill (Kistler Instrument Corp., Amherst, NY) at 1.8 m/s. The standing and walking conditions were both repeated, in the same order, using a close viewing distance. For this NEAR target condition, the visual display was positioned 60 cm from the center of the treadmill and the height was adjusted until the subject verbally responded that the target was at eye level. Each acuity assessment was completed in less than two minutes and all subjects completed the walking trials as part of a single continuous data collection. Prior to, and immediately following these four data collection trials, subjects' acuity was measured using a clinical Landolt C paper chart with a 3 m viewing distance. These tests verified that eye fatigue was not a factor in the results obtained during the other test conditions.

Kinematic Data Collection

While subjects performed the visual acuity assessment tests on the treadmill, the positions and orientations of the head and trunk segments were recorded using four cameras of a video-based motion analysis system (Motion Analysis Corp., Santa Rosa, CA). The segments, represented as rigid bodies, were identified using three reflective markers. A torso harness was used to secure the marker triad to the trunk and an adjustable headband did the same for the head markers. Prior to data collection, a stylus was used to identify the position of specific anatomical landmarks in terms of the local coordinate systems created by the markers on each segment. These transformations were applied during post processing of the data, resulting in the identification of six anatomical landmarks throughout the data trials: the nasal bridge, chin, atlanto-occipital joint, superior surface of the manubrium, seventh cervical vertebrae (C7), and a spot on the lumbar spine. The C7 location and the nasal bridge are of particular interest to the data being reported here are. The latter was used to represent a cyclopean eye position. In addition to the video data that were sampled at 60 Hz, contact switches (Motion Lab Systems, Baton Rouge, LA) secured to the bottom of lab-provided shoes (Converse Inc., North Andover, MA) were monitored using a time-synchronized data stream that was sampled at 300 Hz. The switches were located on the heel and toe of each foot and were used to mark the heelstrike and toe-off events.

Data Processing

Standard Kinematic Measures

Movements of the head in relation to space were quantified using the angular position of the head and the linear motions of the C7 marker. Euler angles for the head were calculated as in previous studies (Moore et al. 1999). The resulting time series data were band-passed filtered, allowing frequencies between 0.25 and 8 Hz to pass without significant attenuation. The data were then segmented into individual strides using right heel contact as the demarcating event. Data from each stride were linearly interpolated to 100 points and a per-stride average was calculated using a minimum of 60 strides per condition. Representative average waveforms for head pitch and C7 vertical translation as well as the head yaw and lateral C7 translation are presented in Figure 2A in the upper and lower panels respectively. The average waveforms were used primarily for qualitative assessments. Peak-to-peak amplitudes for these translation and rotation signals, and the temporal location of the maxima and minima, were extracted from each stride independently. In the case of the vertical translation and pitch signals, where the signals complete two cycles per stride, both were considered in these calculations.

Head Fixation Distance Determination

Measures quantifying individual waveforms provide valuable information about movement patterns. One of the goals of this experiment however, was to quantify the collective contribution of the individual waveforms into a single variable that shows how the combination of the individual waveforms affects the desired goal of gaze stabilization. Building on the concept of a head fixation point during locomotion (Pozzo et al. 1990), Hirasaki et al. (1999) introduced the head fixation distance (HFD). Figure 1 graphically depicts head fixation distance as the distance between the subject and a theoretical plane in space where the trace of the head's point-of-regard is minimized throughout the stride cycle. For the present study, an optimization routine was utilized to determine the location of this plane using Matlab (The Mathworks, Inc., Natick, MA)).

A ray emanating from the head, through the virtual nasal bridge marker was used to calculate the head's point-of-regard on frontal planes at varying distances. The base point of the ray was another virtual marker fixed in the local coordinate system of the head. It was located behind the subject's head and fell on a line segment passing through the FAR visual target and the mean position of the nasal bridge marker during the FAR target standing acuity trial. A way of visualizing the effects of these calculations is to imagine a laser being projected at a fixed angle from between the subject's eyes. A hypothetical intersection between this laser and the NEAR and FAR target planes is shown in the Figure 1 diagram. The per-stride average vertical and horizontal intersections of the head's point-of-regard are shown from the FAR target trial of one subject in Figure 2B. The dark bold line of the time series shown is the intersection on the actual target plane (i.e. the FAR target plane). The other lines are the intersections on hypothetical planes between the FAR target plane and the NEAR target plane. The lighter bold line indicates the NEAR target plane intersection.

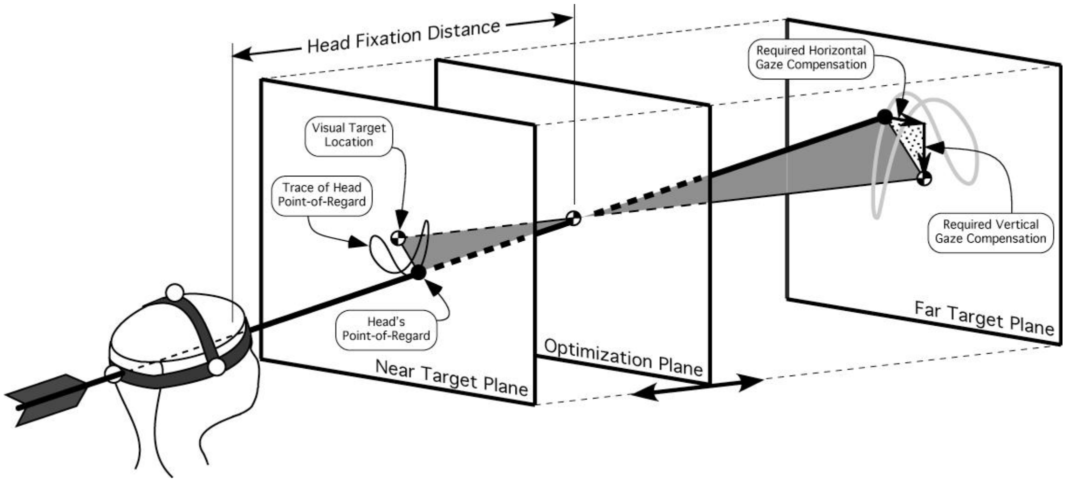

Figure 1: Graphical depiction of the head's point-of-regard and its interaction with planes at varying distances.

Knowing where the head's point-of-regard is relative to the visual target and the orientation of the head for each data point allows the required eye compensation to be calculated. Because the head fixation point is the point at which minimal eye movement is required, these theoretically required eye movements (TREMs) were used in the optimization procedure for determining the location of this point and the distance between the subject and the vertical plane containing the point. Figure 2C shows the TREMs for the signals in panel B. The calculation upon which the optimization was based was the minimization of the RMS amplitude of the TREM through each stride. The TREM was calculated across the entire trial and processed in the same manner as the kinematic variables. Prior to being separated into stride epochs, it was band-pass filtered using the same filter characteristics as before. The stride epochs were interpolated to 100 points, and a fit line between the first and last data point of each stride was subtracted from the stride signal. Following these steps an RMS value was calculated for each stride and an average RMS value was calculated across all strides. A second average RMS value was determined using the strides whose RMS value fell within ±2 standard deviations of the original mean. This procedure was repeated as the

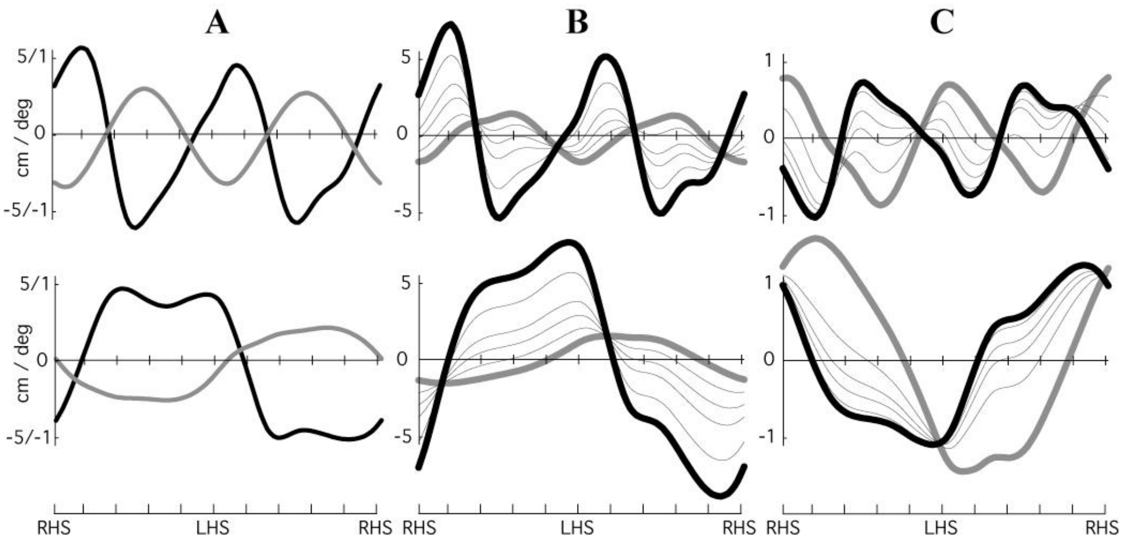

Figure 2: Per-stride average data from the FAR target condition for one subject. The upper row shows movements in the sagittal plane and lower row shows data from the transverse plane. Column A shows the translational movements of the C7 virtual marker (light gray line) and the pitch and yaw rotations of the head (black line). Column B shows the intersection of the head's point-of-regard with planes at various distances. The thick black line represents the FAR target plane and the thick gray line represents the NEAR target plane. Thinner lines correspond with planes at intermediate distances. Column C shows the theoretically required eye movements (TREMs) for the given intersection in Column B.

hypothetical optimization plane was moved toward and away from the subject until the calculated RMS was minimized. This optimization process was repeated while considering only the vertical or horizontal TREMs and the distance between the optimization plane and the subject for these were determined to be the vertical head fixation distance (vHFD) and the horizontal head fixation distance (hHFD), respectively. The process was repeated a third time to find an optimization plane location where the summation of the horizontal and vertical TREM RMSs was minimized. The distance between the subject and the plane considering both TREMs was termed the 3-dimensional HFD (3dHFD).

Visual Acuity Assessment

Assessing subjects' visual acuity was accomplished using custom-written software (LabView, National Instrument, Austin, TX) modeled after the Freiburg Visual Acuity Test (Bach 1996). A more complete description of the methodology and hardware has been published previously (Peters and Bloomberg 2005). Briefly, Landolt Ring optotypes are displayed serially on a computer screen. The subject is required to provide a verbal response corresponding to their perception of where the gap in the ring appears prior to the presentation of the subsequent visual target. Corresponding to the approximate average step time for the given walking velocity, the optotype display time was set to 500 ms. The size of each presented optotype was controlled using a psychophysical PEST (i.e. parameter estimation by sequential testing) procedure (Lieberman and Pentland 1982). This procedure calculates a relative probability that the subject's acuity is at each of the 15 possible optotype sizes following each subject response. The size of the next optotype presented corresponds to the one where the highest relative probability is calculated. The available optotype sizes ranged from –0.4 to 1.0 using steps of 0.1 on the logMAR scale, or 20/8 to 20/200 using the more familiar Snellen scale. In the FAR target condition, the optotypes were displayed on the screen of the laptop computer that was running the software. For the NEAR targets, a microdisplay (Liteye Systems, Highlands Ranch, CO), surrounded by a 30 cm diameter disk, was used. These are shown in Figure 3. The optotypes themselves were bitmap images created using a custom-written Matlab program that created the images using 12-bits of grayscale anti-aliasing to reduce the effects of pixilation. This present study differed slightly from the previous (Peters and Bloomberg 2005) in that 8 possible optotype gap locations were used instead of 4. The resulting reduction in the guess rate allowed the same level of confidence in the acuity measure to be attained using fewer optotype presentations. Twentyfour optotype presentations were used in the threshold determination in the current study, exceeding the 18 viewed as necessary by Bach (1996) to achieve a stable outcome. The orientation of the presented optotypes was pseudo-random. The eight gap locations (i.e. up, down, left etc.) represented four orientations (i.e. vertical, horizontal and the two oblique directions). For each of the four acuity assessments made in this protocol, an equal number of optotypes appeared in the four orientations.

As a post-processing step the subjects' acuity thresholds were re-calculated using the same threshold detection algorithm but while assuming that 75 optotypes were available rather than the actual 15. The result was an acuity measure with a resolution of 0.02 logMAR. Each subject's measured acuity score for each condition was then adjusted to correspond to the actual horizontal viewing distance between the target and the average A-P position of the subject's nasal bridge marker throughout the trial. The resulting acuity scores, as well as other kinematic variables, were compared statistically between the FAR and NEAR conditions using paired t-tests.

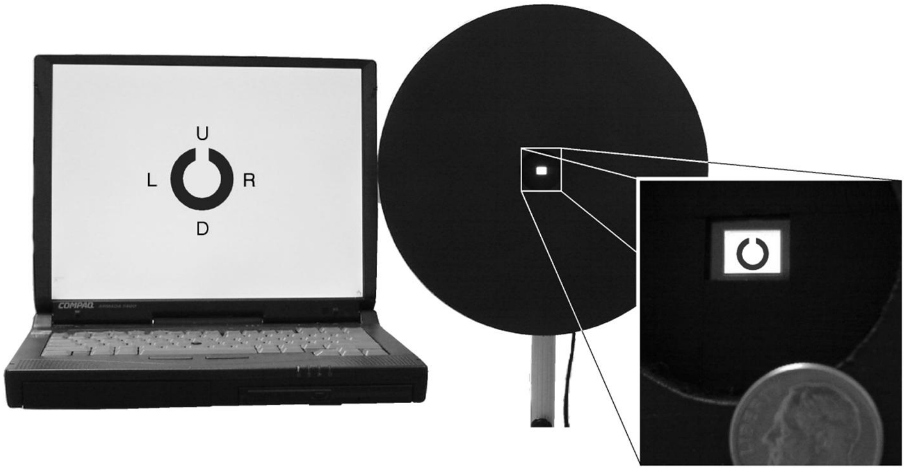

Figure 3: Visual display hardware. The NEAR target microdisplay appears in the middle of a 30 cm disk intended to block visual distraction. The inset shows the microdisplay, with a 0.8 logMAR (i.e. 20/125), next to a US dime.

Results

Kinematics

As expected, based on previous studies, a qualitative assessment of the head pitch and vertical translation revealed a cyclical process that repeated itself once per step, (i.e. twice per stride, see Figure 2A). The relationship between these signals, which has been called "compensatory" in previous studies (Bloomberg et al. 1992; Hirasaki et al. 1999; Moore et al. 1999), existed in the data collected during this investigation as well. As the body translated up, the head pitched down and vice versa. The head yaw and lateral translation signals were also cyclical, but repeated themselves once per stride. These transverse plane signals also showed an anti-phase relationship, with the head yaw being counter to the lateral translation. These relationships are clearly seen in Figure 2A, but a closer inspection shows that their relationships are more complex than just a phase relationship between two sinusoids. It appears safe to assume that the vertical translation signal is nearly sinusoidal. The average difference between the temporal locations of the maximum and minimum values of trunk vertical translation in the FAR condition was 49.72 (C.I. ±1.22) percent of the step cycle. This 50% duty cycle is not shared by the head pitch signal, which appears to be skewed into somewhat of a saw-toothed pattern. On average, the maximum upward head pitch occurs 64.46 (C.I. ±2.78) percent of the step cycle after the minimum. Figure 4 shows the average temporal relationship between the maximum and minimum events for the head pitch and vertical translation signals for both the FAR and NEAR conditions. The relationships, which are not affected by the visual target location, indicate that at the point at which the vertical translation reaches its maximum, the head pitch reaches its minimum (i.e. pointed downward). However, the inverse is not true. The average head pitch maximum lags the vertical translation minimum by an average of 12.54 (C.I. ±2.88) percent of the step cycle. The relationships between signal events in the horizontal direction (i.e. between the translation and head yaw) show less consistency between subjects. The per-stride average waveforms from a majority of the subjects showed the strong presence of higher frequency components in them that changed either the head yaw or lateral translation, or both, into something that was not sinusoidal. An example of this can be seen in the head yaw signal provided in Figure 2A. For this reason, a similar analysis of the temporal relationship between events of the signals was unreliable.

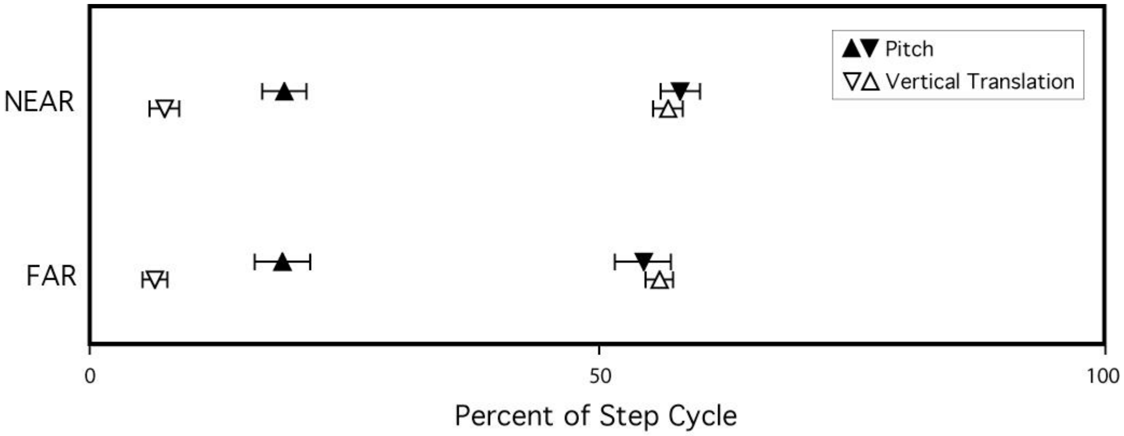

Figure 4: The temporal relationships between the maxima and minima values of the vertical translation (open triangles) and head pitch (filled triangles) signals for the NEAR (upper) and FAR (lower) conditions. Upward and downward pointing triangles indicate the maximum and minimum values, respectively. In the case of the head pitch, maximum refers to the point of highest upward pitch. Error bars represent the 95% confidence intervals.

A peak-to-peak amplitude measure was calculated to characterize the presence of magnitude differences between the FAR and NEAR conditions. The mean head pitch amplitude across all subjects was 3.58 (C.I. ±0.89; range 1.77 to 7.16) degrees in the FAR condition. The mean amplitude for the NEAR condition was 3.96 (C.I. ±0.70; range 2.66 to 6.28) degrees. Eight of the 11 subjects showed an increase in pitch amplitude from the FAR to NEAR conditions, but the difference failed to reach statistical significance ($p = 0.167$).

The head yaw amplitude followed a similar trend. The amplitude increased from 2.85 (C.I. ±0.68; range 1.83 to 5.75) degrees to 3.29 (C.I. ±0.46; range 2.46 to 4.95) degrees from the FAR to NEAR condition. Nine of the 11 subjects showed this trend, but again, the difference failed to reach statistical significance ($p = 0.112$). Differences between conditions did reach statistical significance for the lateral and vertical translation signals ($p = 0.00008$ and $p = 0.0059$, respectively). Rather than an increase in amplitude of the translation signals from the FAR to NEAR conditions, there was a decrease. The mean vertical translation during the FAR condition was 5.43 (C.I. ±0.64; range 3.70 to 7.66) cm compared to 4.85 (C.I. ±0.44; range 3.45 to 6.07) cm in the NEAR condition. The mean lateral translation was 3.56 (C.I. ±0.39; range 2.73 to 4.80) cm in the FAR condition and 3.16 (C.I. ±0.38; range 2.40 to 4.33) cm in the near condition.

Head Fixation Distance

The change in translation and rotation signals seen above, as well as modifications to the movements in other joints or segments of the body, can affect where the head is pointing in space. Measures of Head Fixation Distance (HFD) were used to determine whether the collective actions of the body movements were used to modify the magnitude of the eye movements required for visual fixation between the FAR and NEAR conditions. The results are provided graphically in Figure 5. When only the motions in the sagittal plane are considered in the HFD calculation, the mean for the resulting vertical HFD (vHFD) across all subjects was 1.41 (C.I. ±0.42; range 0.50 to 2.62) m for the FAR condition. The mean was reduced to 0.79 (C.I. ±0.19; range 0.14 to 1.30) m in the NEAR condition. A similar trend existed when the HFD was calculated from movements in the transverse plane. The average horizontal HFD (hHFD) for the FAR and NEAR conditions were 1.37 (C.I. ±0.50; range 0.51 to 3.17) m and 0.47 (C.I. ±0.09; range 0.26 to 0.68) m respectively. As would be expected, a measure that combines the horizontal and vertical directions, the 3dHFD, also showed a reduction during the NEAR target condition compared to the FAR condition. The mean 3dHFD in the FAR condition was 1.34 (C.I. ±0.39; range 0.51 to 2.57) m and was 0.71 (C.I. ±0.13; range 0.39 to 1.13) m in the NEAR. All subjects showed a reduction in the 3dHFD in the NEAR condition. On average the subjects NEAR 3dHFD was 59 (C.I. 12; range 29 to 94) percent that of their FAR 3dHFD values. Paired t-test comparisons between the FAR and NEAR conditions for all three of the HFDs resulted in p-values less than 0.003.

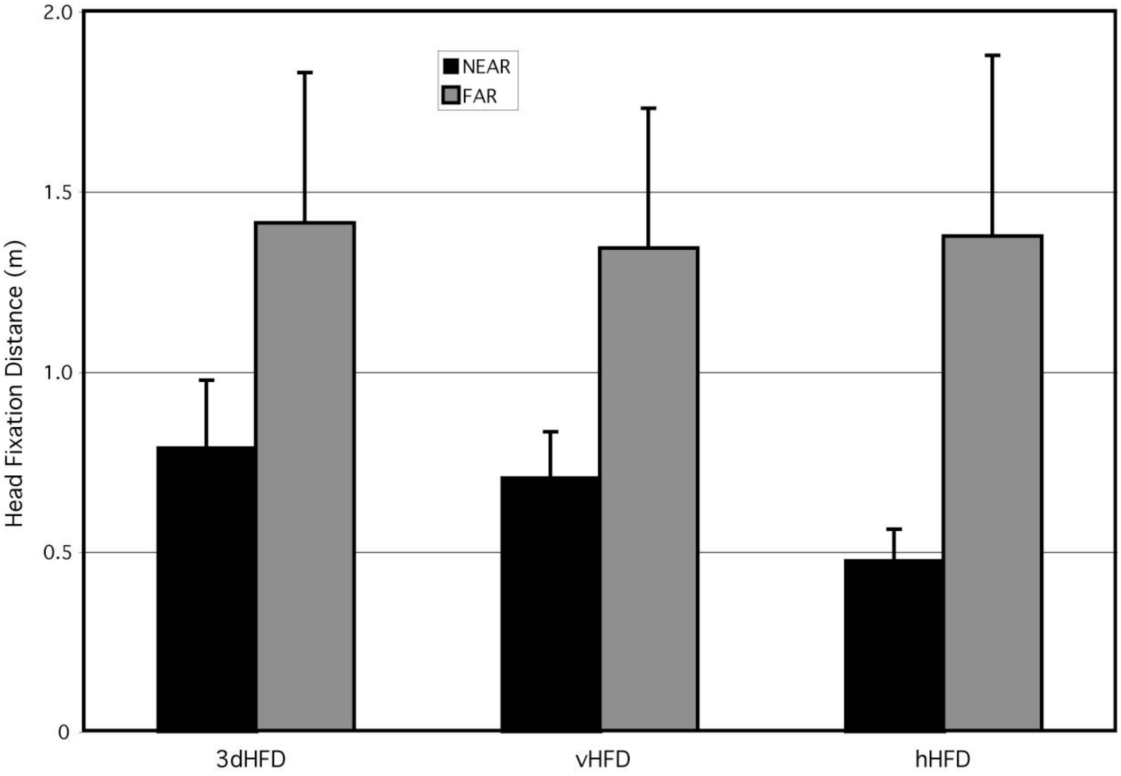

Figure 5: Group means for the 3dHFD, vHFD, and hHFD for the NEAR and FAR conditions. Error bars represent the 95% confidence intervals.

The nearer the optimization plane is to the target plane, the smaller the amplitude of the required eye movement. Therefore, the reduction in the 3dHFD for the NEAR target condition served to reduce the magnitude of the required eye movements in this condition. This is shown graphically in Figure 6. The three TREMs in the figure represent data from the

FAR and NEAR target walking trial. The two thicker lines are derived from the FAR condition. The dark one shows the TREM on the actual target plane (i.e. the FAR target plane) and the lighter one shows the TREM on a hypothetical NEAR plane. If no change in the coordination of the body segments occurred, the thick gray line shows the average eye movement trace that would be required in the NEAR condition. The thin black line shows the actual average TREM trace derived from the NEAR walking trial. These traces clearly show the contribution of the non-ocular mechanisms to the gaze stabilization task in the NEAR condition.

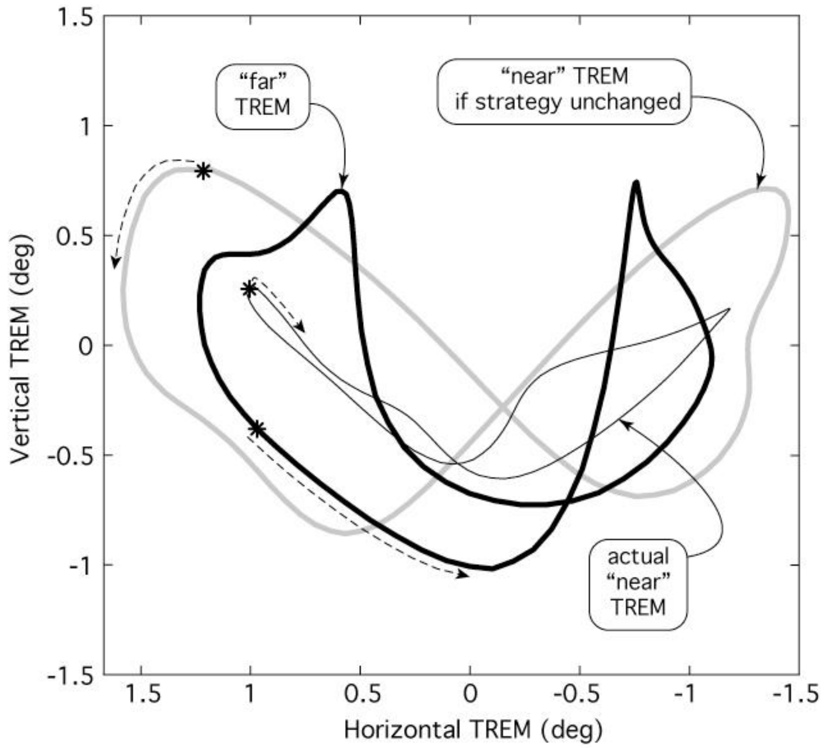

Figure 6: Graphical representation of the TREMs for the FAR (thick black line) and NEAR (thin black line). The gray line shows what the TREM would be for the NEAR condition if the coordination of the non-ocular mechanisms remained unchanged between conditions. The asterisks mark the point of right heelstrike and the dotted arrow lines end at the 10% mark of the stride.

Visual Acuity

The true measure of the effectiveness of the combined contributions of both ocular and non-ocular gaze control mechanisms is whether or not the visual target was stabilized while walking. The goal of the acuity measures collected in this investigation was to assess how well the image was stabilized. Figure 7 shows the average acuity measures across all subjects. The measures obtained during the walking trials are shown relative to the standing acuity using units that represent the number of lines on a clinical eye chart. The data indicate that acuity is maintained while walking and fixating the target in the FAR condition (mean: -0.06; C.I.: 0.32; range: -0.6 to 1.1). Interestingly, 8 of the 11 subjects registered a slight to moderate improvement in acuity while walking. In contrast, all of the subjects showed a decrement in acuity while walking and fixating the NEAR target. The average decrement in this condition was 1.46 (C.I.: 0.47; range: 0.4 to 3.0) eye chart lines. These results are consistent with unsolicited subject reports of oscillopsia only in the NEAR condition.

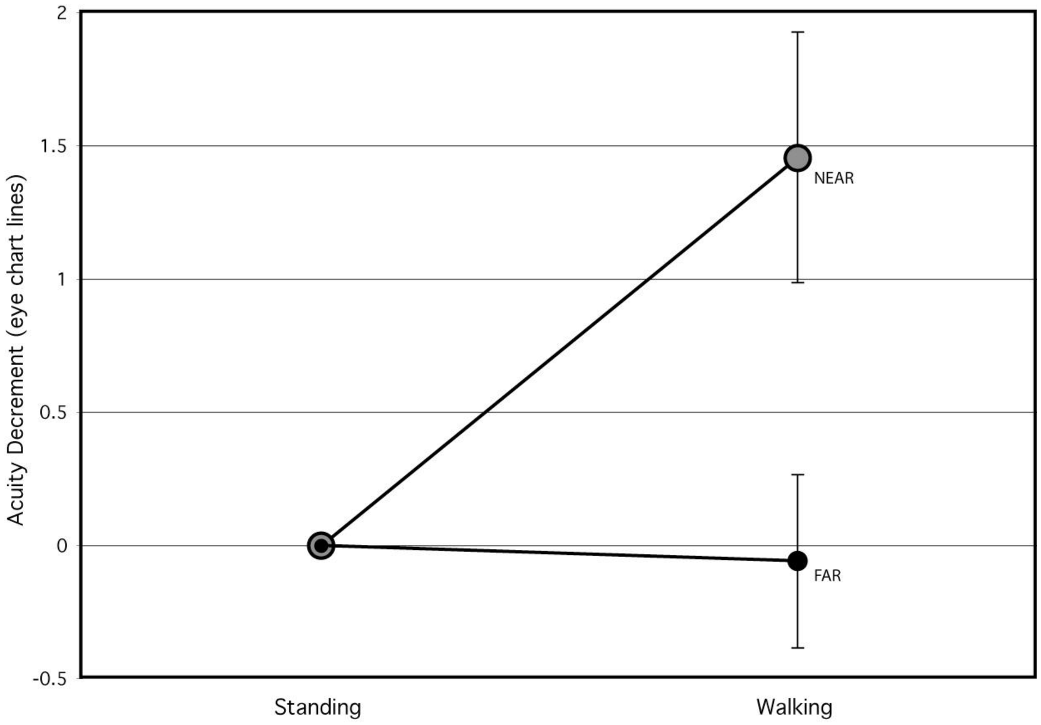

Figure 7: Visual acuity results from the FAR (black circle) and NEAR (gray circle) target viewing conditions. Data are shown relative to each subject's standing condition for the appropriate target distance. Error bars represent 95% confidence intervals.

Discussion

The main findings of this investigation are that non-ocular degrees of freedom coordinate themselves to contribute to a gaze stabilization task while walking, but despite this reorganization, visual acuity is compromised while walking and viewing a NEAR target. In addition to these results, data showing the temporal relationships between maxima and minima of the vertical translation and head pitch signals indicate that the interaction between the two is more complex than a simple case where head rotation compensates for body translation. This complexity is extended to the projection of the head's three-dimensional point-of-regard which never achieves a single head fixation point regardless of the location of the theoretical projection plane. This holds true when motions in a single movement plane are considered (i.e. either the sagittal or transverse plane motions).

The calculations of head fixation distance (HFD) used in this investigation indicate that movement patterns in the head and/or body were being adjusted to facilitate the goal of stabilizing gaze. This was true when single plane motions were considered or when the combined effects of both motion planes were considered together. Statistically speaking, these adjustments were primarily the result of changes in the translation components of the motion. The fact that changes in the peak-to-peak amplitude of the head pitch did not reach statistical significance is in contrast with the results presented by Bloomberg et al. (1992). Consider however that a high majority of subjects in the present study did show an increase in the measured rotational motions of the head in addition to the decreases in translation amplitude. The increase in head rotation and decrease in translation both bring the head fixation point closer to the target in the NEAR condition and therefore reduce the magnitude of the required eye movement response. The result of these changes was a mean decrease in 3dHFD of approximately 40% when changing from the FAR to NEAR viewing conditions. The reduction in the 3dHFD measure is similar to the reduction in the vHFD values (see Figure 5). This change is larger than the one reported by Moore et al (1999) for the vHFD. Differences in the reported changes in vHFD could be the result of differences in walking speed, visual target viewing distances, inter-subject variability, or more likely a combination of these factors. Hirasaki et al. (1999) showed consistent HFD measures at walking speeds above 1.4 m/s while fixating a target at 2.0 m, but the interaction between walking speed and target distance was not directly investigated. Regarding the visual target viewing distances, the Moore et al (1999) study showed a relatively consistent increase in vHFD for targets ranging from 0.25 to 2.0 m. It appears however that the 2.0 m viewing distance may have imposed a ceiling effect on subjects in Moore at al. Four of the 11 subjects in the current study had vHFD values that exceeded the largest values reported in the Moore at al. study and 2 of these 4 had vHFD that exceeded 2.5 m, more than a half meter beyond the furthest visual target used by Moore at al. Despite these differences, the results from both studies indicate that the non-ocular mechanisms are re-organized in a way to minimize the required eye-movements for NEAR targets.

The difference in visual acuity between the standing and walking condition for the NEAR target trials suggest that although non-ocular, and presumably ocular (Moore et al. 1999), modifications were made in an attempt to fixate the target, these changes did not adequately compensate for the viewing condition while walking. The decrement in acuity during the NEAR condition reported here represents nearly 1.5 lines on a clinical eye chart (i.e. 0.15 logMAR). Although such a decrement may not at first seem dramatic, a change in acuity of one eye chart line represents a change in optotype size of slightly more than 25%. The 1.5 line decrement reported here is less dramatic than the nearly 2.5 line decrement reported earlier (Peters and Bloomberg 2005). Part of this difference might be explained by the fact that in the current study, the acuity values were corrected for the actual viewing distance. This was not done previously. Prior to this correction, the raw acuity values in the present study were greater than 2 lines. For the FAR viewing distance, the mean visual acuity values for the group of subjects were not different between the standing and walking conditions. From this result, it would be easy to assume that the ocular and non-ocular gaze stabilization systems provided adequate compensation to allow visual fixation while walking and viewing FAR targets. However, because the optotypes were visible for the duration of the step cycle, the recorded acuities for both viewing conditions represent the best acuity during the step cycle. It could be the case that visual compensation, and therefore visual acuity, is not consistent throughout the step cycle.

While the current paradigm does not allow for an assessment of whether acuity is consistent throughout the step cycle, there is evidence that the interaction between the head and trunk segments is complex. Sagittal plane motions, where most of the attention has been focused in previous literature, are far more complex than a simple interaction between two 180° phase-shifted sine waves. It is not simply a vertical trunk input and a compensatory head pitch response. One piece of evidence for this argument is the temporal relationships between the maximum and minimum values of the vertical translation and the head pitch signals presented in Figure 4. The average per-stride waveforms presented in Figure 2B provide further evidence. The theoretical plane intersections of the head's point-of-regard never approach the straight line that would be present if the theorized head fixation point was stable throughout the stride cycle. Moore et al. (1999) pointed out that the vHFD was not consistent during the stride, but the periodicity of the intersection between the head's point-of-regard and any theoretical plane between the subject and the FAR target in the current protocol suggest that the head fixation point travels in a systematic manner during the stride cycle. Systematic can imply simplicity, but in this case it is the result of a complex interaction and what's more, it imposes additional complexity on ocular control.

Eye movement recordings while walking can be difficult to obtain, but electrooculographic (EOG) and video eye movement records have both revealed a phase-reversal of the eye movements with respect to the head pitch during NEAR target fixation (Peters et al. 1996; Moore et al. 1999). This phase change can be interpreted based on the movements that provide the primary threat to visual stabilization. For FAR targets, it is predominantly the head pitch that must be compensated for, while for NEAR targets it is the vertical translation that plays the larger role. Moore et al. suggested a transfer of oculo-motor control from an angular vestibulo-ocular reflex (aVOR) to a linear VOR (lVOR) to account for this change. It is clear that angular and linear motions are both present regardless of target distance so it is the relative weighting of the aVOR and lVOR inputs that would be adjusted when viewing targets at different distances. Assuming that this is so, the relative weighting would be dependent on the visual target viewing distance and the HFD. It would also depend on the magnitudes of the linear and angular movements from which the HFD is derived. The inter-subject differences in HFD and the magnitudes of the movement components comprising HFD, as well as the changes in HFD within each stride, are likely some of the sources of the variability in aVOR gains measured by Crane and Demer (1997). The complexity of the required eye movement response gives credence to these authors' assertion that measures of angular VOR gain during locomotion are not a "fair measure of ability to stabilize visual images".

In summary, the results of the current investigation provide further evidence that gaze control during locomotion is a whole-body task. Gibson (1979) theorized regarding this likelihood and recent evidence from individual movement degrees of freedom (Mulavara and Bloomberg 2002) and the current results of a collective variable (e.g. 3dHFD) support this idea. Regardless of the number of coordinative patterns that could emerge to facilitate gaze fixation in the NEAR target condition used in the current investigation, the direct measure of visual acuity suggests that the patterns used and the corresponding eye movements were not completely effective. Whether extended exposure to the NEAR target condition could result in an oculo-motor adaptation response or a refined non-ocular coordination pattern to improve a subject's ability to walk and visually fixate a NEAR target is unknown. Future studies of the adaptive modifications in this condition as well as further study into the complex head-trunk interaction and oculo-motor control during locomotion could help facilitate rehabilitative programs for patients who experience oscillopsia during walking.

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