Human Gait at Sea While Walking Fore-Aft vs. Athwart

Eric Haaland; Jeffrey Kaipust; Yi Wang; Nick Stergiou; Thomas A. Stoffregen

BACKGROUND: Sea travel leads to well-known changes in gait, but these effects have not been evaluated using quantitative data obtained through controlled experiments. We obtained quantitative data on step-timing patterns as experienced maritime crewmembers walked on a ship at sea.

METHODS: Using a within-subjects design, crewmembers walked back and forth along straight line paths (11 m long) that were parallel with the ship's long (i.e., fore-aft) and short (i.e., athwart) axes. Using contact switches attached to the feet, we measured temporal parameters of gait, including stride time, the variability of stride time, and the coefficient of variation. We also evaluated the temporal dynamics of stride times using detrended fluctuation analysis.

RESULTS: The variability of stride time differed between walking fore-aft (mean = 0.10 s) and walking athwart (mean = 0.28 s). The coefficient of variation also differed between walking fore-aft (mean = 11%) and walking athwart (mean = 43%).

CONCLUSIONS: We obtained direct evidence that ship motions in roll and pitch differentially affect the timing of stepping patterns in human gait. This novel finding motivates new research on quantitative parameters of gait at sea.

KEYWORDS: gait, human performance at sea, motor control, adaptation.

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Travel on the open sea is characterized by complex, oscillatory motion of ships in three dimensions of translation (surge, sway, and heave) and three dimensions of rotation (roll, pitch, and yaw). For passengers and crew the ship is the base of support, or ground surface: control of the body must be adjusted to compensate for the 6 degrees of freedom oscillatory motion of the ship.[2,14,17] One of the most widely known aspects of this compensation is changes in gait that characterize persons who have fully adjusted to life at sea. Anecdotal accounts focus on a "rolling gait" that is sufficiently pronounced that it can be seen by casual observers.[14]

Despite its antiquity and ubiquity, human gait at sea has not been analyzed in terms of quantitative kinematics. Existing research has focused on observational or self-report data relating to motion-induced interruptions.[6,7] Studies of human performance at sea have not included quantitative measures of gait kinematics.[2,17] In this article, we report an experimental study of the quantitative kinematics of human gait on a ship at sea. We used methods that are standard in research on terrestrial gait in terms of equipment, procedures, dependent variables, and analysis.

Ship motion differs in roll and pitch. The control of upright stance is powerfully affected by variations in body orientation relative to a ship at sea. When facing fore-aft, ship motion in pitch is in the body's anterior-posterior (AP) axis while ship motion in roll is in the body's mediolateral (ML) axis. When facing athwartship, this relationship is reversed. On a ship at sea, the simple manipulation of facing in one direction rather than the other can have powerful effects on the control of standing body posture, on subjective perception of bodily stability, and on the coordination of postural activity between individuals. Chen and Stoffregen[5] measured the quantitative kinematics of standing body sway on a ship at sea while maritime crewmembers stood while facing fore-aft versus athwart. Overall, body sway was greater when facing athwartship than when facing fore-aft. In addition, when facing athwart postural sway tended to be greater in the body's ML axis and less in the body's AP axis, as is commonly the case on land, but when facing fore-aft this relation was qualitatively reversed, such that sway was

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greater in AP and less in ML. Differences in roll and pitch might also give rise to differential effects in stepping patterns during walking. In the present study, we evaluated this question in a group of experienced crewmembers.

METHODS

Subjects

The study protocol was approved in advance by the Institutional Review Board at the University of Minnesota and informed consent was obtained from each subject. Participating in the study on a volunteer basis were 10 individuals, comprising 6 men and 4 women, ranging in age between 23 and 62, in height from 1.52 to 1.88 m (mean = 1.73 m), and in weight from 52.16 kg to 127.01 kg (mean = 75.07 kg). As part of the informed consent process, each subject indicated that they had no history of dizziness, seizures, gait disorders, or vestibular dysfunction.

Apparatus and Experimental Setting

The study was conducted on board the R/V *Thomas G. Thompson* during a transit from Honolulu, HI, to Seattle, WA. The ship was 83.5 m long with a 16-m beam. It displaced 3051 tons and cruised at 11 kn. This ship was the location for several of our earlier studies on postural control.[5,18,19] On each day at sea, we recorded ship motion continuously from midnight to midnight. Ambient temperature and noise were out of our control and crewmembers occasionally passed through the labs and passageways to conduct duties. However, our project was the only organized activity being conducted in the areas in which we were located. Data were collected on a single day (the fifth day at sea) between 09:00 and 16:00.

To monitor stepping patterns we use electronic contact switches (1.25-cm diameter force-sensitive resistors, Delsys, Natick, MA). One resistor was affixed to the underside of each shoe at the heel. Flexible wires connected the resistors to samplers attached to the leg just above each ankle. The sampler units communicated wirelessly with a data logger unit, which was carried by the subject in their preferred hand. Each resistor was sampled at 1000 Hz.

Testing was conducted in the interior of the ship's main deck, such that the horizon was not visible. Two 11-m walking paths were marked on the deck surface, as illustrated in **Fig. 1**. The fore-aft path was entirely within in the ship's main laboratory, which was 22.9 m long and 6.1 m wide. The marked walking path was 6.25 m to starboard from the ship's centerline. The athwart path began in the main lab, extended across a passageway and into the ship's computer lab. The paths traversed working areas of the ship, such that diverse equipment and systems were within the field of view. However, there were no obstructions to normal gait along the marked paths.

We monitored ship motion using the accelerometer in an Apple Macbook pro laptop computer, using Seismac (http://www.suitable.com/tools/seismac.html). The accelerometer was sampled at 25 Hz in each of three linear axes (surge, sway, heave). The accelerometer was not sensitive to angular motion. On the day of testing, accelerometer data were collected continuously over successive 12-h periods.

Procedure

The experiment was conducted on the fifth day of the transit. After completing the informed consent procedure, the subject was seated and we affixed the sensors to the soles of their shoes. For each trial, the subject was asked to walk back and forth along the length of one of the walking paths at a comfortable pace for 8 min. Each subject completed one 8-min trial in each of the two conditions. The order of conditions was alternated across successive subjects.

Data Analysis

For each trial, following previous studies,[8] we analyzed the complete dataset, including both straight-line walking and turns as subjects walked back and forth. Raw data from the resistors were downsampled to 100 Hz and stored using EMGworks® (Delsys, Natick, MA). For each leg, the stride interval was calculated as the time between consecutive heel strikes; that is, there were two separate stride intervals for each complete step cycle. We analyzed three distinct aspects of the walking data. First, for each trial we computed the variability of the time series of stride intervals (operationally defined as the standard

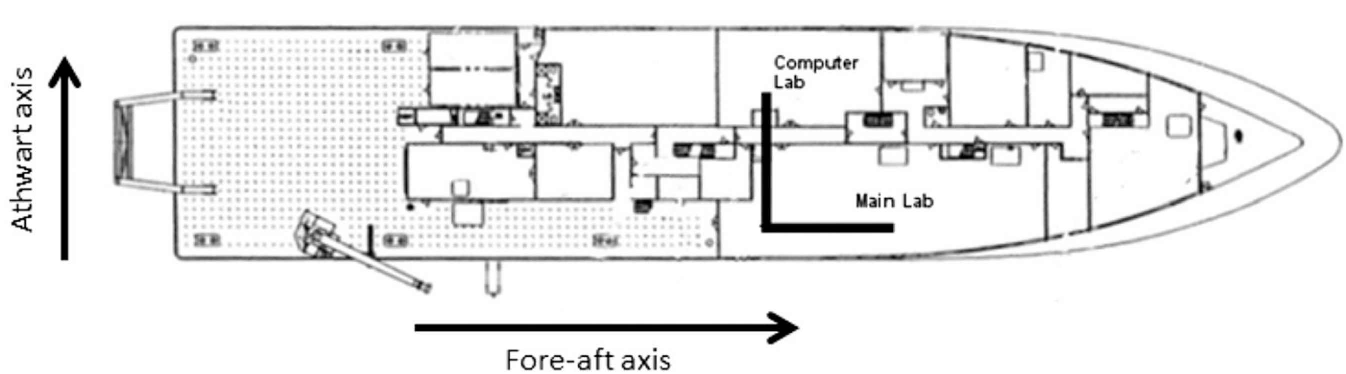

Fig. 1. Experimental setting. The walking paths are indicated by the heavy black lines that form a right angle extending into the Main Lab and the Computer Lab. The fore-aft path was entirely within the Main Lab, while the athwart path extended from the Main Lab into the Computer Lab.

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deviation of the time series of stride intervals). Second, for each trial we computed the coefficient of variation (operationally defined as the standard deviation of stride intervals divided by the mean stride interval for that trial). Finally, for each trial we analyzed the temporal dynamics of stride intervals. To do this, we subjected the time series of stride intervals for individual subjects to detrended fluctuation analysis, or DFA. DFA describes the relationship between the magnitude of fluctuations in postural motion and the time scale over which those fluctuations are measured.[4] DFA has been used in laboratory studies of postural sway in upright stance[11] and in laboratory studies of stride intervals in gait.[3] We conducted inferential tests on α, the scaling exponent of DFA. The scaling exponent is an index of long-range autocorrelation in the data, that is, the extent to which the data are self-similar over different time scales. White noise, which is uncorrelated, yields $\alpha = 0.5$. The presence of long-range autocorrelation is indicated by $\alpha > 0.5$. Pink noise (also known as 1/f noise) is indicated when $\alpha = 1.0$. Values of $\alpha > 1.0$ indicate nonstationary activity that resembles a random walk, while $\alpha > 1.5$ indicates Brownian noise. We did not integrate the time series before conducting DFA. For each dependent variable we compared walking in the two conditions using paired samples *t*-tests.

RESULTS

There were no motion-induced interruptions: each subject was able to walk continuously for the duration of each trial. On the day of testing and on each of the preceding days at sea, the sea state was 7 on the Beaufort scale,[1] a 10-point scale used to characterize surfaces waves and swell. On the scale, 0 corresponds to a flat calm and 10 corresponds to wave motion during a hurricane. On this cruise, the roughness arose from steady trade winds rather than from a storm. On the day of testing, the magnitudes of the primary peaks in ship oscillation were −15, −17, and −23 dB along the heave, sway, and surge axes, respectively.

The stride time intervals did not differ between the fore-aft condition (mean = 0.92 s, SD = 0.13 s) and the athwart condition (mean = 0.75 s, SD = 0.20 s; $P > 0.05$). For the variability of stride time intervals, the difference between the fore-aft and athwart conditions was significant ($t^9 = 3.47$, $P < 0.01$, 95% CI = 0.063–0.30) (**Fig. 2**). The effect of conditions was also significant for the coefficient of variation ($t^9 = 3.13$, $P = 0.12$, 95% CI = 0.09–0.56) (**Fig. 3**). By contrast, the temporal dynamics of stride time intervals did not differ between the fore-aft (mean $\alpha = 0.56$, SD = 1.49) and athwart (mean $\alpha = 0.56$, SD = 0.22) conditions ($P > 0.05$).

DISCUSSION

We conducted a controlled analysis of the dynamics of human gait during walking on a ship at sea. We monitored the temporal intervals between footfalls as experienced maritime crewmembers walked along paths that were aligned with the fore-aft or athwart axes of the ship. The results revealed that patterns of step timing differed as a function of walking direction relative to the ship. These results offer new insight into the nature of adaptations in human movement that occur on ships at sea.

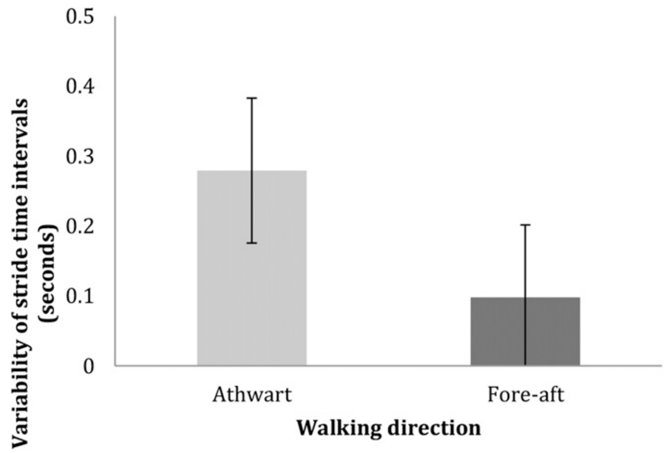

Fig. 2. Stride time variability as a function of walking direction. The error bars represent the 95% confidence interval of the mean.

Walking direction (walking parallel to the long versus short axes of the ship) affected the variability of stride intervals (Fig. 2) and the coefficient of variation (Fig. 3). In each case, greater variability was associated with walking parallel to the athwart axis. These findings are consistent with the fact that, in general, ship motion in roll is greater than ship motion in pitch. The finding that gait differed as a function of walking direction is compatible with studies showing that standing body sway and overall bodily stability differ when facing fore-aft versus facing athwart.[5]

We instructed subjects to walk "at a comfortable pace." This instruction left open the possibility that walking speed might have differed between the fore-aft and athwart directions. However, stride time intervals did not differ as a function of walking direction. Thus, our results do not provide support for the hypothesis that subjects chose different walking speeds in the fore-aft and athwart conditions.

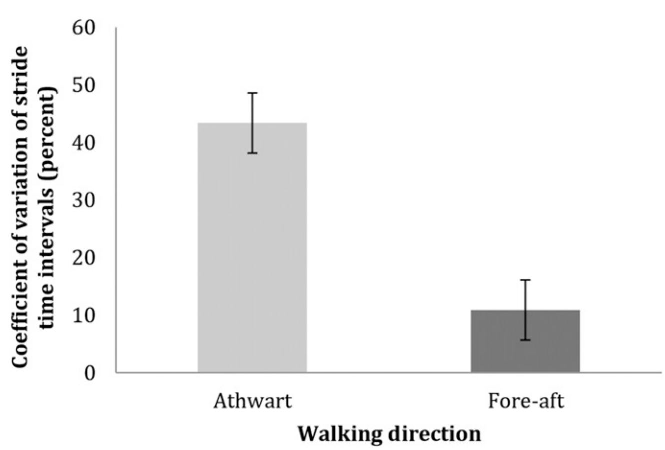

Fig. 3. The coefficient of variation as a function of walking direction. The error bars represent the 95% confidence interval of the mean.

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We found no evidence that our manipulation of walking direction influenced the temporal dynamics of stride intervals. Thus, the results of the present study are compatible with the hypothesis that motion of a ship in its fore-aft and athwart axes differentially affects the timing but not the temporal dynamics of stepping patterns. This possibility motivates future research on gait at sea that can directly address this issue. Studies of standing body sway on ships at sea have sometimes found different effects in analyses of spatial and temporal aspects of sway.[5,15] Given the widely accepted assumption that there are close connections between posture and gait,[13] it would be interesting, in future research, to obtain comparable measures of posture and gait on ships at sea.

Ship motion along its midline (either fore-aft or athwart) differs from motion in parallel directions that are offset from the midline. For example, when walking along a ship's fore-aft midline, ship motion in roll will be exclusively angular, whereas when walking parallel to, but offset from the ship's fore-aft midline (as occurred in the present study), ship motion in roll will include both linear as well as angular components. For this reason, we might expect patterns of gait to differ not only as a function of walking direction, as in the present study, but also as a function of the distance of a given walking path from the ship's midline. In future research, it will be interesting to examine the quantitative kinematics of gait for walking along paths that are at different distances from a ship's midline.

A classic anecdotal report is that gait at sea differs from gait on land, which suggests a comparison between data collected in these two settings. In principle, data collected at sea might be compared with normative data from land-based studies. For example, for healthy young adults walking at preferred speed on land, the coefficient of variation typically is 1–3%.[9,12] These values differ dramatically from our findings, which might suggest that ship motion greatly magnifies the coefficient of variation of gait.

We regard any such interpretation as both premature and inappropriate. The principal reason for our caution is the fact that our subjects were maritime crewmembers, with years of experience working on ships at sea. Lengthy experience controlling gait at sea might lead to general changes in gait patterns. That is, patterns of gait learned at sea might persist on land. Another possibility is that there may be self-selection bias. Experienced maritime crewmembers are, by definition, persons who have successfully adapted to life on a moving surface. It may be that this particular type of adaptability characterizes a relatively small proportion of the general population. In this regard it is important to recall that there are large individual differences in susceptibility to seasickness.[10,15] These differences complicate comparisons between the general (i.e., terrestrial) population and persons who are insusceptible to seasickness. In light of these considerations, the only appropriate way to compare "gait on land" with "gait at sea" would be through experiments using within-subjects designs.

Life at sea imposes changes on the organization of human gait, an effect that has been richly documented in anecdotal reports over thousands of years. We conducted an experimental study of the influence of ship motion on the timing of step patterns. On a ship at sea, we recorded the time series of stride intervals as experienced maritime crewmembers walked along the fore-aft and athwart axes of the ship. Walking axis affected the variability and the coefficient of variation of stride intervals, but did not appear to influence the temporal dynamics of stride intervals. Many anecdotal reports confirm that gait at sea differs from gait on land. However, our finding that gait at sea was affected by variations in the direction of walking (relative to structural axes of the ship) appears to be novel. Our study can be understood as a demonstration showing that technology-based methods for laboratory-based gait analysis can be used to quantify the kinematics of gait on ships at sea.[16] As such, our study raises more questions than it answers. Our effects raise questions about how gait at sea is organized to respond flexibly and rapidly to variations in ship motion, and about how such situation-specific flexibility is acquired as novices get their sea legs.

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