A CINEMATOGRAPHIC ANALYSIS OF TREADMILL RUNNING BY EXPERIENCED MALE COLLEGE DISTANCE RUNNERS

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High-speed cinematography affords the investigator the opportunity to analyze motions that would not be possible otherwise. The ability to capture movements on film and slow those movements to a more visually manageable speed, has greatly increased the precision of movement analyses.

The topic of this study is a cinematographic analysis of treadmill running, utilizing a two-camera technique for the data collection. Four kinematic variables of the treadmill running pattern were determined directly from this film, and two kinematic variables were derived from a three-dimensional film analysis procedure. It was the thesis of this investigation that although overground running for most individuals is a fairly natural means of locomotion, initial treadmill running is not as natural. Thus, a certain amount of treadmill training may be needed to familiarize the runner with treadmill locomotion and provide consistency to his/her treadmill running pattern.

OVERGROUND-TREADMILL CONTROVERSY

Since the turn of the century, many human locomotion studies have been completed. These studies have provided significant information about human walking and running patterns. In an effort to control the environment or because of the measuring equipment used, several locomotion variables have been observed under simulated conditions with the use of a treadmill. There is in the current literature, however, a controversy between the actual similarity of treadmill locomotion as compared to overground locomotion in terms of both physiological and biomechanical factors. It has become apparent that several inherent differences between the two running modes, such as wind and surface friction, must first be accounted for before making any direct comparison.

Biomechanical measures

In a review of mechanical energy states of movement, Winter (1978) outlines several important biomechanical differences between treadmill and overground locomotion:

1. Treadmill gait has an absolute velocity of zero in absolute space, whereas overground gait has a positive absolute velocity . . .
2. While in stance the overground walker has zero velocity between his foot and the floor. Thus there is no possibility for transfer of energy to the floor [Energy could be transferred to the floor if the overground walker is observed from a reference frame that is moving at constant velocity parallel to the walker]. However, on a treadmill during stance the foot has a horizontal velocity, which when combined with the horizontal reaction force represents mechanical power . . .
3. [There is virtually no difference in the path of the center of gravity when walking on a level or inclined treadmill, because at the end of each step the body returns to the same height. Obviously, work is being done in lifting the body up a hill, but the actual difference between walking up a hill and up a positive treadmill incline depends upon the observer's frame of reference-fixed or moving.]
4. There was sufficient evidence to show from Nelson et al (1972) that the energy patterns associated with treadmill running will be somewhat different than for overground movement. (pp. 194-195)

Dillman (1975), in his review of kinematic analyses of running, cautioned against interpreting running data from the two different running modes, and indicated throughout the review from which mode the running characteristics had been observed. The two major biomechanical studies of treadmill/overground running differences included in Dillman's review were from Dal Monte et al (1973) and Nelson et al (1972). The study by Dal Monte and associates reported no outstanding differences between overground and treadmill running as long as the speed is close to competition speeds. They did find less vertical displacement of the body and shorter strides on the treadmill. However, their purpose was to determine if the treadmill could be used as a simulator for middle distance running. The purpose of Nelson's et al study was specific to the controversy, and the differences that they found between overground and treadmill running were significant. Several other factors presumably contributed to the different results obtained from these two investigations. Dal Monte et al hypothesized that the rather extensive treadmill training (24 weeks, totalling 30 hours) their subjects had contributed to the similarities they observed. While Dal Monte and colleagues used three subjects, Nelson et al used sixteen experienced distance runners who were given six treadmill practice sessions prior to filming.

The variables analyzed in the two preceding studies were different. Nelson et al (1972) determined stride length, stride rate, stride time, times of support and non-support for all 16 subjects and vertical and horizontal velocities of the center of gravity for nine of the sixteen subjects. Dal Monte and

associates (1973) studied the aerial, dumping and extension
phases, stride length, and movement patterns of the ear lobe,
shoulder, elbow, hand, hip, and knee. These variables were
analyzed using one camera for sagittal viewing and a large mirror
for frontal viewing, while Nelson et al used one high speed
camera for sagittal viewing only. Other factors which may have
contributed to the different conclusions include wind, and tread-
mill and overground surface differences. Nelson et al filmed
both overground and treadmill running indoors, and stated that
the frictional characteristics of the treadmill belt and running
ramp were "reasonably similar" (p. 234). Dal Monte et al filmed
their treadmill running indoors and the overground running over
an outdoor track. Although neither study statistically corrected
for wind and surface differences, an attempt was made by Nelson
and colleagues to minimize these effects.

Brandell and Williams (1974) studied the differences
between floor and treadmill walking using cinematographic and
electromyographic techniques. "Treadmill-floor differences were
found to be nonsignificant at the .05 level for most of the limb
motion data" (p. 94). They did find a "small but consistent
tendency for velocity and stride length to be greater on the
floor or track than on the treadmill" (p. 74), at the higher
speed. This was thought to be a consequence of the restrictive-
ness of the short treadmill. They concluded that the treadmill
could be validly used for determining motion data.

The purpose of a study by Elliott and Blanksby (1976) was
to determine whether differences existed in stride length, stride
rate, time of support, and time of non-support for overground and
treadmill running. They filmed (sagittal view) 12 male and 12
female regular joggers, who were also experienced treadmill
runners, over track and treadmill conditions. Although speeds
were matched from track to treadmill, no corrections were
utilized for equalizing conditions on the basis of wind or
surface friction differences. Results of Elliott and Blanksby's
(1976) study indicated no significant difference in any of the
four stride variables between overground and treadmill running
at the slower speeds, but "significant differences were recorded
for the period of non-support, stride length and stride rate"
(p. 86), at the faster velocities. Both males and females
decreased stride length and increased stride rate on the tread-
mill at faster speeds. While differences between the two
running modes were found, they were contradictory with those
findings of Nelson et al (1972). For example, Nelson et al
found the stride length to increase and the stride rate to de-
crease with horizontal treadmill running at the higher velocities.
They also found the time of support to always be greater with
the treadmill condition. It is not clear if this opposite
finding of stride length and rate relationship is due to
differences in procedures, subjects, measurements, or some other
contributing factor.

In a more recent overview of the treadmill-overground issue, Van Ingen Schenau (1980) attributes the observed controversy in part to the "coordinate system which implicity or explicity is used" (p. 257). He suggests, as does Margaria (1976), that apart from air resistance the treadmill locomotion mechanics are not fundamentally different from locomotion on a boat, airplane, or train, as long as both systems move at constant velocity. With respect to the treadmill itself, Van Ingen Schenau suggests that to help insure constant speed, the belt should be somewhat rough for proper friction, and the treadmill motor strong enough to absorb the resistance offered by the belt while the subject walks or runs. Van Ingen Schenau also notes that auditory and, to a greater extent, visual differences between overground and tread-mill locomotion be somehow experimentally equated. He further mentions that initial treadmill locomotion can be rather stressful, especially for children. Ideally, the treadmill belt should be an integral part of the floor. Van Ingen Schenau's nine to sixteen year old subjects showed much longer double support periods when walking on a treadmill elevated one meter above the floor as compared to overground walking.

This limited review has shown the need for future research into the treadmill-overground controversy. However, several inherent differences between the two running conditions must first be adequately investigated, before an exhaustive, full scale treadmill-overground study is undertaken. These general inherent differences between the two running modes are (a) surface friction, (b) wind condition, (c) visual or kinesthetic feedback, (d) surface height, and (e) relative subject velocity. Two related concerns must also be investigated. These are (a) the notion of energy being derived from the motor-driven treadmill belt (this has not been completely substantiated nor refuted), and (b) the amount of previous treadmill training given to the subject.

Some of these contributing factors have been adequately studied but few results have actually been incorporated into the design of any of the aforementioned treadmill-overground investigations. In view of the fact that the treadmill is used extensively as an overground simulator in a number of disciplines, it has become important to ascertain the exact similarities and differences between the two running conditions. One can realize that many factors can contribute to the differences between treadmill and overground locomotion in terms of energy consumption and stride patterns. Of particular concern in the present investigation is the idea of subject treadmill familiarity.

Treadmill familiarity

Treadmill familiarity is defined as a state obtained when the subject has had sufficient exposure to treadmill locomotion such that no inconsistencies in the gait process are evident. This condition is contingent upon two related processes, which are described by Charteris and Taves (1978) as an initial treadmill

adjustment, and a subsequent long term conditioning. The concept of treadmill familiarity raises two relevant questions. Would a lack of subject treadmill exposure contribute to any significant kinematic differences that might result from a treadmill-overground comparison? Secondly, how much treadmill exposure or training is necessary before a consistent gait pattern is established? Few biomechanical investigations were found that were concerned with subject treadmill familiarity.

The amount of treadmill training given subjects, particularly in the studies of overground-treadmill differences, was quite inconsistent. Nelson et al (1972) gave their 16 subjects six treadmill training sessions prior to filming them. They assumed:

> That six practice periods were adequate to allow the subjects to adjust to the treadmill. Subjective observation and the reactions of the subjects indicated that after the practice periods they had adjusted to performing on the treadmill and ran in a comfortable and relaxed manner. (p. 234)

Dal Monte and colleagues (1973) gave their subjects 24 weeks of treadmill running for a total of 30 hours, prior to filming. Elliott and Blanksby's (1976) college students "were regular joggers as well as being experienced treadmill runners having had in excess of ten training sessions on the treadmill" (p. 85). Neither Elliott and Blanksby's nor Nelson and associates' (1972) study indicated how many total hours of treadmill training their subjects received. Cavanagh et al (1977), in describing limitations to their biomechanical study of elite and good distance runners, noted differences among subjects in the amount of treadmill familiarity:

> Some athletes had previous experience and were at ease with the procedure while others were experiencing treadmill running for the first time. This may have affected the patterns of motion recorded. (p. 342)

Bates, Osternig, Mason, and James (1978, 1979) studied the lower extremity function during treadmill running of 21 subjects. In an effort to minimize differences that might exist between treadmill and overground running, all subjects participated in three supervised training sessions prior to being filmed.

Williams (1981) gave his 31 recreational runners a five day acclimation period to treadmill running prior to taking physiological and film data. His subjects ran 30 minutes each day at a similar pace to that of testing speed. With the different amounts of treadmill exposure given to subjects in these investigations, it is apparent that further study would be needed to ascertain the amount of treadmill training that would be required to produce a consistent treadmill locomotion pattern.

ALTERATIONS IN THE RUNNING PATTERN

While kinematic changes have been charted in the development of the running patterns of children (Clouse, 1959; Beck, 1966;

Matsui, 1973; Brown, 1978; Fortney, 1980), other studies have
reported changes that occur in athletes as a result of fatigue
(Sprague & Mann, 1980; Haven, 1977; Sparks, 1975; Adrian &
Kreighbaum, 1973), and long-term training (Nelson & Gregor, 1976).

Two studies were found that investigated the mechanical
changes of treadmill locomotion (Charteris & Taves, 1978; Wall &
Charteris, 1980). From film data, Charteris and Taves (1978)
analyzed kinematic "cyclograms" of eight novice treadmill
walkers. The purpose of the investigation was to determine if
alterations occurred in the walking cyclogram patterns at
selected time intervals of a single 15 minute treadmill exposure
period. Initial adjustment to the treadmill was termed
accomodation and consisted of a "faltering balance-regaining
'tripping' in the first steps taken" (p. 664). Subsequent
adjustment (usually after ten seconds) was denoted as habituation,
and was indicative of a constant gait pattern and "replicable for
a given subject from day to day" (p. 661).

Cyclogram comparisons were made between the novice treadmill
walkers and those of a subject assumed to have been completely
habituated by virtue of having walked and run on the apparatus
for several years (Charteris & Taves, 1978). Although the
novice walkers had "accomodated, i.e., developed an essentially
normal and fairly stable pattern given this initial exposure"
(p. 664), the gait lacked constancy of the order exhibited by the
experienced treadmill subject. In light of this finding, Charter-
is and Taves concluded that the 15 minute training period was
an inadequate time for novice treadmill subjects to produce a
consistent, stable treadmill walking gait. As a result of this
investigation, and further substantiated by Wall and Charteris
(1980), two pertinent recommendations for future study were
reported: (a) how long the process of complete habitiuation to
treadmill walking takes (whether days or weeks), and (b) how
rapidly in habituated subjects, the initial accomodation to the
treadmill is made (whether within 10 seconds or more).

METHODS

The purpose of this study was to determine if changes occurred
in selected treadmill stride variables as a result of treadmill
training. Six experienced male college distance runners, who
gave informed consent, volunteered as subjects. The subjects
had a mean age of 21.7 years (SD 1.1), mean height of 182.8 cm
(SD 8), and mean mass of 66.8 kg (SD 4.6). Their best mean
collegiate (track or road condition) 5K race time was 15:42, and
best 10K mean time was 33:12. Prior to the first day's training
run, the subjects, who were novice treadmill runners, were given
an instructional demonstration of treadmill running, and of
mounting and dismounting the moving treadmill belt. At this
time, the subjects were allowed to walk on the treadmill at a
slow speed for 15 s. In this way, the subject's naivety to
treadmill running was maintained.

Training and filming protocol

The daily treadmill training workload for this study was 4.0 m/s, on a level treadmill (Quinton, model 24-72) for 15 minutes. This workload was selected to minimize the fatigue factor which has been shown to affect running mechanics (Adrian & Kreighbaum, 1973; Sprague & Mann, 1980), yet allow for some adaptation effect which occurred with treadmill walkers (Charteris & Taves, 1978; Wall & Charteris, 1980) over one 15 minute treadmill period. Subjects ran on the treadmill the same time each morning on Mondays through Fridays for two consecutive weeks (10 days total). No workouts preceded the morning treadmill run except a five minute overground warm-up jog and five minutes of stretching.

Each day, body landmarks and segments were marked with a black felt tip marker according to segmental locations of college aged males proposed by Dempster (1955), and appropriate for Knudson's (1980) 17 segment rigid-linked digitizing-computer program. Following the first day's marking, subsequent landmark identification generally consisted of darkening the original mark from day to day. Markings were positioned for frontal (anterior subject side) and right-side sagittal viewing.

Two Photo-sonics 16mm movie cameras, loaded with 400 ASA Kodak B-W 4-X reversal film, operating at 64 frames/s, were used for all filming sessions. The cameras were mounted on leveled Hercules tripods and positioned at right angles to each other, so that the lens apertures were 7.97 m (frontal) and 7.42 m (sagittal) from the subject. The heights of both lens centers were adjusted to the approximate center of the running subject, 1.57 m above the floor. Artificial lighting was used to provide a film exposure time of 1/300th s. From a large sweep second hand clock, placed in the field of both camera views with a 45 degree mirror, the actual camera speeds were determined to be 63.5 frames/s ($\pm$ .5 frames/s). The clock was also used to synchronize events occurring between views, as was a stroboscopic flash, that was triggered periodically during each filming stage.

The runners were instructed to run at the controlled treadmill speed of 4.0 m/s (3.96 - 4.04 m/s), and to maintain the same relative position at the center of the film planes toward the front of the treadmill belt. Subjects were filmed three times during each daily 15 minute period at the training times of 1, 8, and 14 minutes. The cameras reached their peak speeds in two seconds and ran approximately five more seconds at each filming stage. This camera operating time was determined to be adequate from a pilot filming attempt and provided about 15 to 20 strides from which the analyses were made.

Film analysis

Six kinematic stride variables were determined from the film. Collectively, these measurements were thought to be

reflective of the running style in light of variables previously examined. It was also anticipated that these kinematic factors would represent sensitive measures to running pattern changes that would occur over time. The stride variables utilized in this study were stride length and rate, stride time, time of support and time of non-support, and vertical and lateral horizontal displacement of the center of gravity. The temporal and stride length variables have been used in a number of locomotion studies (Cavanagh, Pollock, & Landa, 1977; Dillman, 1975; Hogberg, 1952; Nelson, Dillman, LaGasse, & Bickett, 1972; Nelson, & Gregor, 1976), while the three-dimensional center of gravity displacement variables provide relatively unique locomotion information.

Approximately 17 strides from each film session were available for analysis. Because right-left asymmetries in the running stride may exist (Cavanagh et al, 1977), more than one stride needed to be analyzed to provide a representative or average stride for any one training time of the study. The average kinematic variable from four consecutive strides (strides 8, 9, 10, and 11) was used for determining the temporal and stride length variables while two consecutive strides (strides 9 and 10) were used to determine the average center of gravity displacements. Stride length and temporal data for the selected strides were determined by frame count with a Vanguard Motion Analyzer. Errors associated with foot position interpretation and synchronizing events between frames were considered to be negligible. The treadmill running speed used for determining stride length was calculated from a marked reference point on the treadmill belt.

The vertical and lateral horizontal displacements of the center of gravity were found by using a sonic digitizer-computer system (Science Accessories Graf/Pen Digitizer Unit and Hewlett-Packard 2100 Microprogrammable Computer). The digitizing software programs and program for determining the total body center of gravity were originally developed and validated by Knudson (1980). These programs were appropriately modified for facilitation of the present investigative stride variables. Approximately 50 frames elapsed during two consecutive treadmill strides at 4.0 m/s. Because of computer storage limitations it was decided that every other frame from both views be digitized. This procedure provided nearly 25 three-dimensional positions of the center of gravity during the two strides. The reliability coefficient for determining center of gravity positions was .99. The vertical displacement of the center of gravity, used in the statistical analyses, was the mean difference between the highest and lowest measures recorded during the two strides. The mean difference between the two most extreme positions of the center of gravity in the horizontal direction (as observed from the frontal view) was deemed the lateral horizontal displacement of the center of gravity.

The kinematic stride variables for the six subjects over the ten days of treadmill training were plotted as a function of the training day and time period. The data were statistically tested with a trend analysis of variance procedure (Furguson, 1976). This test correlated the group mean variables for the ten days with two sets of orthogonal polynomials, linear and quadratic, to determine if the shape of the plotted histograms were indeed significant. The trends were tested for significance, using the square of the correlation coefficients in the analysis of variance.

RESULTS

Within-day changes

It was the thesis of this investigation that treadmill stride patterns would change as a result of treadmill training. Kinematic variables were plotted for Minutes 1, 8, and 14 of each day's treadmill run. Histograms for stride length and rate, and center of gravity displacement (Figure 1) illustrate slight
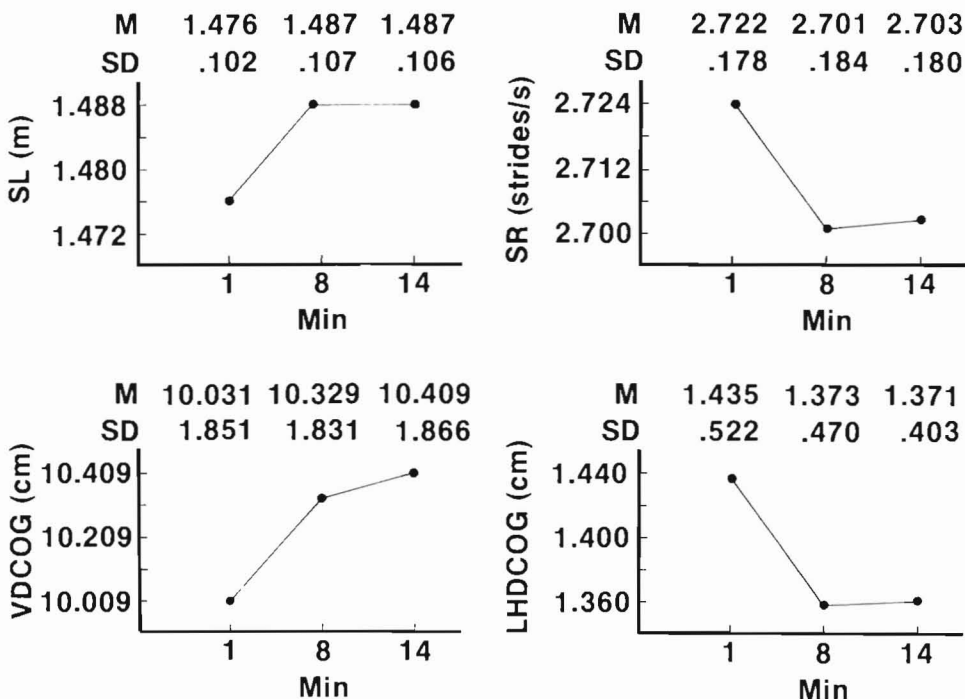

Figure 1. Histograms of daily changes in treadmill stride length and rate, and vertical and lateral horizontal displacement of the center of gravity.

changes that occurred over 10 daily 15 minute treadmill runs. Small changes were also shown to occur in the temporal variables. These accomodating changes to treadmill running tend to concur with the fluctuating walking "cyclograms" originally proposed by Charteris and Taves (1978) and later by Wall and Charteris (1980). However, the trend analysis of variance, used in the present investigation, revealed that neither a significant ($p > .05$) nor quadratic trend existed between minute one and fourteen.

Alterations over ten days

Analysis of variance was used to determine if a significant day-to-day trend existed in the treadmill running stride variable day means for Minutes 1, 8, and 14. Neither a linear nor a quadratic trend existed in the treadmill variables measured over the two week treadmill training period. Further, no significant differences were recorded between any two days of the training period. Graphical plots were drawn to depict the day-to-day trends of the stride variables (Figure 2). With the exception of support time, which tended to increase over the ten day period, the stride variables followed the same daily trends as previously observed in the within-day analysis.

Individual subject profiles suggest differences in treadmill running style in terms of both amount and direction of stride alterations over the ten day training period. This is illustrated by contrasting the stride lengths of Subject One with Subject Four (Figure 3). While Subject One showed a marked increase in stride length, especially from day one to day two (9 cm), Subject Four's stride length tended to decrease (3 cm). The other subjects and their stride variables described similiar different individual trends.

DISCUSSION

Looking at the individual subject profiles, it is seen that the runners select their own stride length and rate for a given speed. The product of stride length and stride rate equals running velocity (Dillman, 1975). Where Subject One chose a faster stride rate and shorter stride length on the first day, Subject Four ran at a slower stride rate and longer stride length, to run at the same speed. Opposite tendencies in running style like these, would tend to average or negate any significant group trend, regardless of whether or not the variables were determined relative to subject physique (e.g. height to stride length ratio). It is probable that both the small sample size and the unique characteristics which differentiated the runners, contributed to the insignificant statistical findings.

In speculating why an adjustment to a new modality might exist, if indeed it does, one would be compelled to think that an initial fear of the treadmill (Van Ingen Schenau, 1980) might generally cause the runner to shorten the stride and consequently
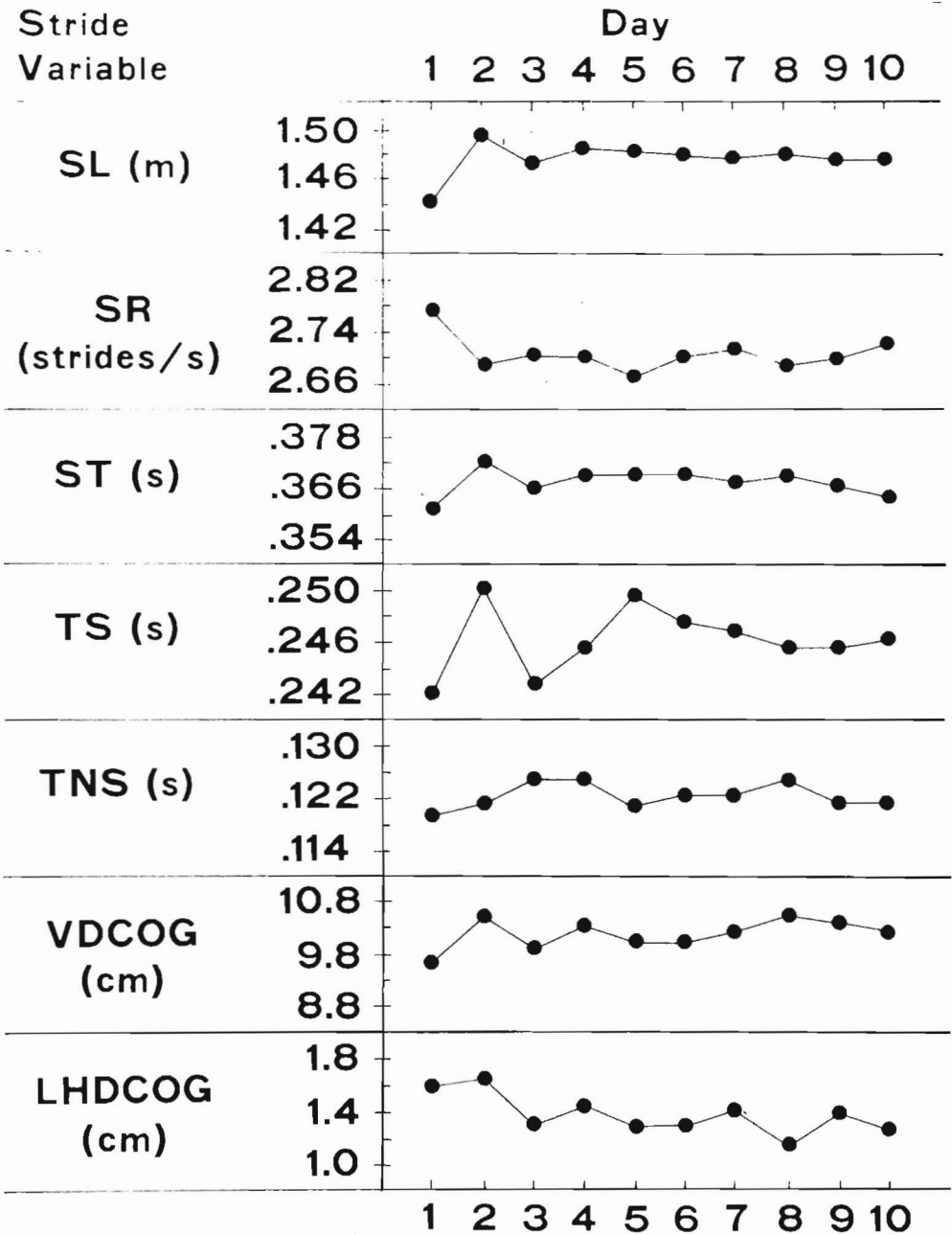
Figure 2. Day-to-day trends of seven kinematic stride variables during treadmill training (N = 6).
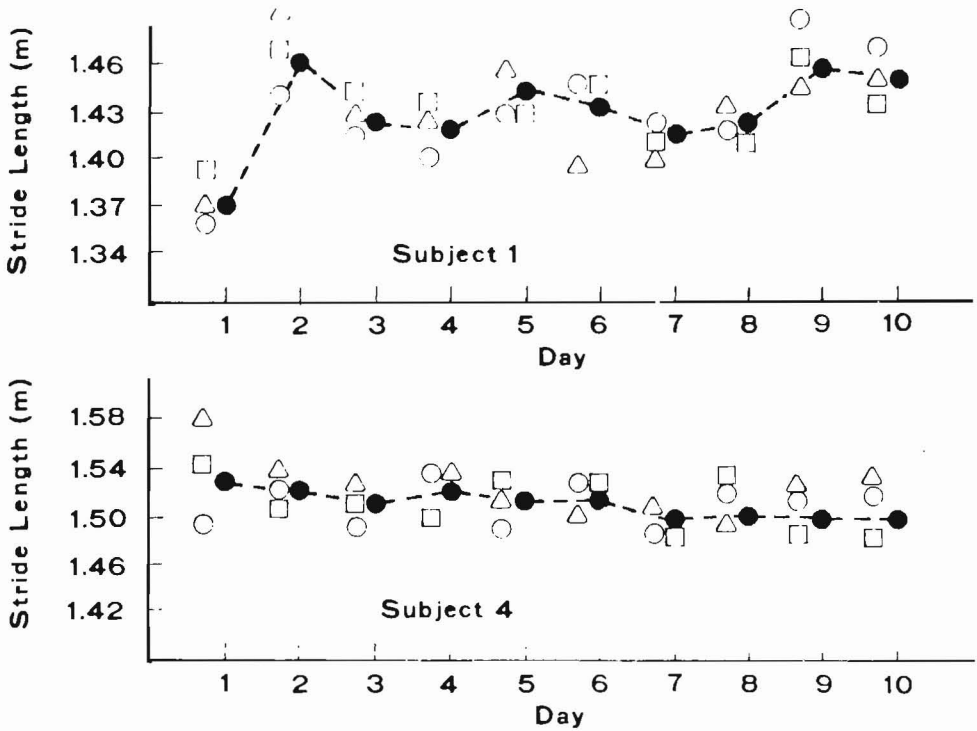
Figure 3. Treadmill stride lengths of Subject One and Subject Four. Min 1=○, Min 8=△, Min 14=□, Day X̄=●.

increase the stride frequency, as a measure of caution. While the histograms suggested small changes in stride length and rate tendencies, the theory of initial treadmill adjustments was not statistically supported. If novice treadmill subjects are found to adjust or accomodate to the treadmill mode of locomotion, it would be interesting to examine if physiological steady state running, which usually occurs during the early minutes of distance running (Astrand, 1977), coincides with biomechanical adjustments such as stride length and rate (Hogberg, 1952). It could be assumed that slight changes in the running stride might exist in a treadmill run until a physiological steady state exists, in which case, the runner becomes comfortable with the surrounding conditions and the pace.

Stride time, together with the component phases of non-support time and support time, are thought to reflect rhythm or style (Cavanagh et al, 1977; Nelson & Gregor, 1976). No

significant differences were found in any temporal measure
within the daily or across the 10-day treadmill session. Under
these treadmill conditions, the average stride time was
approximately .37 s, while the mean times of support and non-
support were .25 s and .12 s, respectively. Perhaps the neuro-
muscular development of the runner's overground stride pattern
was so engrained that the treadmill mode posed little difference
to the support and non-support stride components.

It was anticipated that a novice treadmill runner would
gain lateral stability in the early stages of treadmill training.
While the subjects tended to decrease the amount of lateral
horizontal displacement of the center of gravity from Minute
One to Minute Fourteen, and also over the ten day training
period, the decrease was not significant. The subject's center
of gravity vertical displacement was shown graphically to increase
daily from Minute One to Minute Fourteen, and also over the ten
day treadmill training period. These vertical and lateral
horizontal center of gravity displacement findings were consistent
from subject to subject, but were not statistically significant
to the .05 level.

Further study would be needed to substantiate the indications
of the histograms and the earlier findings of Charteris and Taves
(1978) and Wall and Charteris (1980). When one considers that the
range of the ten day combined subject means for stride length
at Minute One, for example, was 1.41 to 1.49 meters, and the
SD nearly 10 cm, it could be assumed that the differences due
to the treadmill training would be quite small, if they existed,
but perhaps not entirely negligible. The major overground/tread-
mill biomechanical findings (Nelson et al, 1972; Dal Monte et al,
1973; Elliott & Blanksby, 1976) are inconclusive about stride
differences and similarities that exist between the two locomotion
modes. It is likely that providing the subject with an adequate
amount of exposure to the treadmill would at least lessen the fear
of treadmill locomotion, especially with novice treadmill subjects
and children (Van Ingen Schenau, 1980). Further, it is possible
that differences found between treadmill and overground stride
patterns could be attributed in part to small accomodating changes
occurring with first exposure to the treadmill apparatus, in
addition to other factors such as surface friction and wind
differences.

The amount of previous overground running experience of the
present sample may have contributed to the insignificant altera-
tions that occurred over the ten day and intra-day treadmill
training periods. Perhaps changes would occur in the treadmill
stride of inexperienced overground runners whose running styles
are not so completely formulated. Within the limitations of the
study, it was concluded that statistically significant changes
did not occur, either within-day or over ten days, in stride
length, stride rate, stride time, time of support, time of
non-support, lateral horizontal displacement of the center of
gravity, or vertical displacement of the center of gravity, of

six experienced male overground distance runners, who trained 15
minutes daily on a treadmill operated at 4.0 m/sec. Future
studies of treadmill familiarity should include larger sample
sizes from a variety of running populations, more sensitive
measures of data collection and reduction (e.g. phase locked
cameras and data smoothing techniques) and a more highly
sophisticated statistical design.

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