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Measurement of Step Widths and Step Lengths: A Comparison of Measurements Made Directly From a Grid With Those Made From a Video Recording

James C. Wall, PhD[1]
Julie Devlin, BS, PT[2]
Rhonda Khirchof, BS, PT[2]
Brian Lackey, BS, PT[2]

INTRODUCTION

For those involved in the assessment of gait, there are many systems currently available that provide objective data on kinetic and kinematic gait variables. Force plates, electromyography, and electrogoniometers are just a few examples of the instrumentation that can be used by therapists to analyze gait in the clinic.[3,10,11] Unfortunately, many of the systems used to obtain these measurements are not practical for a variety of reasons, including their complexity, high cost, time requirements, and space dependencies. Consequently, the vast majority of therapists and others involved in the day-to-day assessment and treatment of gait disorders rely on their observational skills alone. It has been demonstrated that the quality of such assessments depend upon the experience of the therapist.[8] A number of studies have also cast doubt on the reliability and validity of these subjective assessments.[12,14,16] Video recording has been suggested as a way of enhancing the observational skills of the clinician.[17] Even with this extra and useful tool, videotaped observational gait analysis has been shown to be only slightly to moderately reliable when data from different observers are compared.[5]

Physical therapists often assess and treat patients with locomotor disability. In many instances, it would be useful to gather objective data on the spatial gait variables of step length and step width in these patients. Patients with stroke, for example, tend to have step length asymmetries,[18] as do patients who suffer from painful joints in the lower limbs.[13] In addition, elderly persons who have a history of falling often have both step length and step width abnormalities.[9] Typically, clinicians will subjectively assess step lengths, step length asymmetry, and base of support. Objective measurement of these spatial variables may be made directly from imprints left on a surface that a subject has walked across. One such technique uses felt-tipped markers taped to the back of the patients' shoes.[1] The measurements from the marks left on the walkway are time-consuming to obtain. To overcome this problem, Robinson and Smidt[15] developed a technique for the measurement of step lengths as the subject walked. The basis of this technique used a grid-pattern constructed from masking tape, which was stuck onto the floor. The tape covered an area 10 m × 0.3 m. The masking tape was then ruled off in 3 cm increments along its length. To assist in identifying exactly where the foot made contact with the ground, the lines were numbered sequentially. As the subject walked, the clinician noted the positions of the feet along the line of progression, and from these, determined step lengths. This is most easily

[1] *Professor, Department of Physical Therapy, University of South Alabama, Mobile, Ala.*
[2] *Department of Physical Therapy, University of South Alabama, Mobile, Ala.*
The protocol for this study was approved by the Institutional Review Board at the University of South Alabama.
Send correspondence to James C. Wall, Department of Physical Therapy, University of South Alabama, Room 1214, 1504 Springhill Avenue, Mobile, AL 36604. E-mail: jcwall@jaguar1.usouthal.edu

done for patients with short step lengths and very slow walking speeds. For nonimpaired subjects, the technique is problematic because of the increased cadence and the consequent decrease in time between footfalls. Gaudet et al[6] were able to measure step lengths and step widths by videotaping subjects walking over a grid of 5-cm squares. The advantage of this technique was the ability to freeze the video to more accurately determine the position of the foot on the grid, which had numbers stenciled on it. The drawbacks of the study were that a short walkway was used and the technique required the camera operator to follow along behind the subject. The authors[6] noted that these problems were most acute when the technique was used to measure subjects at fast walking speeds. From a clinical standpoint, this technique would be improved if a longer walkway could be used and filming could be done without the need to walk behind the subject with a camera. The purpose of our study was to examine the validity and reliability of measurements of foot placements taken from a specially designed walkway grid with a color-coding system, simplifying position estimation. This would be done by comparing the positions estimated from the video with those obtained by directly measuring the positions from ink marks left on the grid.

METHODS

Eight volunteers, 2 men and 6 women (32 ± 19.19 years of age, varying from 20 years to 72 years and functional ability) were used as subjects in the filming portion of this study. Six of the subjects with no known gait pathologies were selected from the student body at the University of South Alabama. The remaining 2 subjects, each with a gait pathology, were recruited from the community. One subject had post-polio syndrome and a leg length asymmetry; the other was an elderly woman with compromised balance. Neither of these 2 subjects used an assistive device. These 2 subjects were included to provide a variety of functional abilities in the sample. All subjects wore comfortably fitting clothing and athletic footwear. Prior to participating in the study, all subjects were informed about the study and each signed a consent form. The study, including the consent form, had been approved by the Institutional Review Board of the University of South Alabama.

A computer was used to draw a grid of 10-cm squares of alternating gray and white color. The grid was further divided into 5-cm squares using thinner lines. On the major lines outlining the larger squares, marks were placed at 1-cm intervals along and across the grid, as can be seen in Figures 1 and 2. The grid also had a center line that was used in the measurement of step widths. The walkway was constructed by sticking a series of these grids to the floor, covering an area of 6 m × 0.75 m. At either end of this central region, a 2-m section without the grid markings was added to allow for speed increases and decreases at the start and finish of a walk. The edges of the central region of the walkway were color-coded so that each metered section was clearly identifiable when viewing the videotape (Figures 1 and 2). The grid walkway was covered with clear adhesive plastic for protection and so that the ink marks could be wiped away following each walk. Using double-sided adhesive tape, modified stamp pads that left the imprint of a small arrow were taped to the rear plantar surface of the shoes. The points of the arrows on these ink pads were aligned with marks, or self adhesive dots of contrasting color, on the backs of the shoe. These marks, or dots, were centrally located and close to the bottom of the shoe, as can be seen in Figure 1. These dots, which could be clearly seen from behind, were used to determine the positions of the feet on the grid when viewing the video. For video measurements made along the length of the walkway, the positions of the backs of the heels, viewed from the side, were used as shown in Figure 2. A roll-on inker was used to apply ink to the pads.

Two camcorders were used to videotape the subjects as they walked, as can be seen from the schematic diagram of the walkway and camcorders shown in Figure 3. The side-view camcorder was placed midway along the walkway, 5 m to the side, to record the positions of the footfalls along the walkway in the line of progression. These measurements would be used to determine step lengths. This camcorder was panned as the subject walked, and the zoom was set such that both feet were always in the field of view. The camcorder that was set up at the end of the walkway allowed for measurement of the positions of foot placements that fell either side of the midline, from which step width could be determined. A shutter speed of 1/500 s was used on both camcorders to get clearer images when the recording was replayed in slow motion and freeze-frame modes.

Each subject was given a brief explanation of the procedure prior to testing. Ink was applied to the stamp pads and the subject was positioned at the start of the walkway. Each subject walked once at each of the self-selected slow, medium, and fast speeds. For each walk, the walking speed and stride times were determined using a multi-memory stopwatch.[21] Stride times were determined by clicking the lap button on this stopwatch each time the right foot made contact with the ground in the central region of the walkway. From these data, the mean stride time was calculated. After the walk, one investigator determined the positions along and across the grid for each ink mark directly from the grid. Once these measurements were made for each step taken, the ink marks were erased and the subject was set up to walk again.

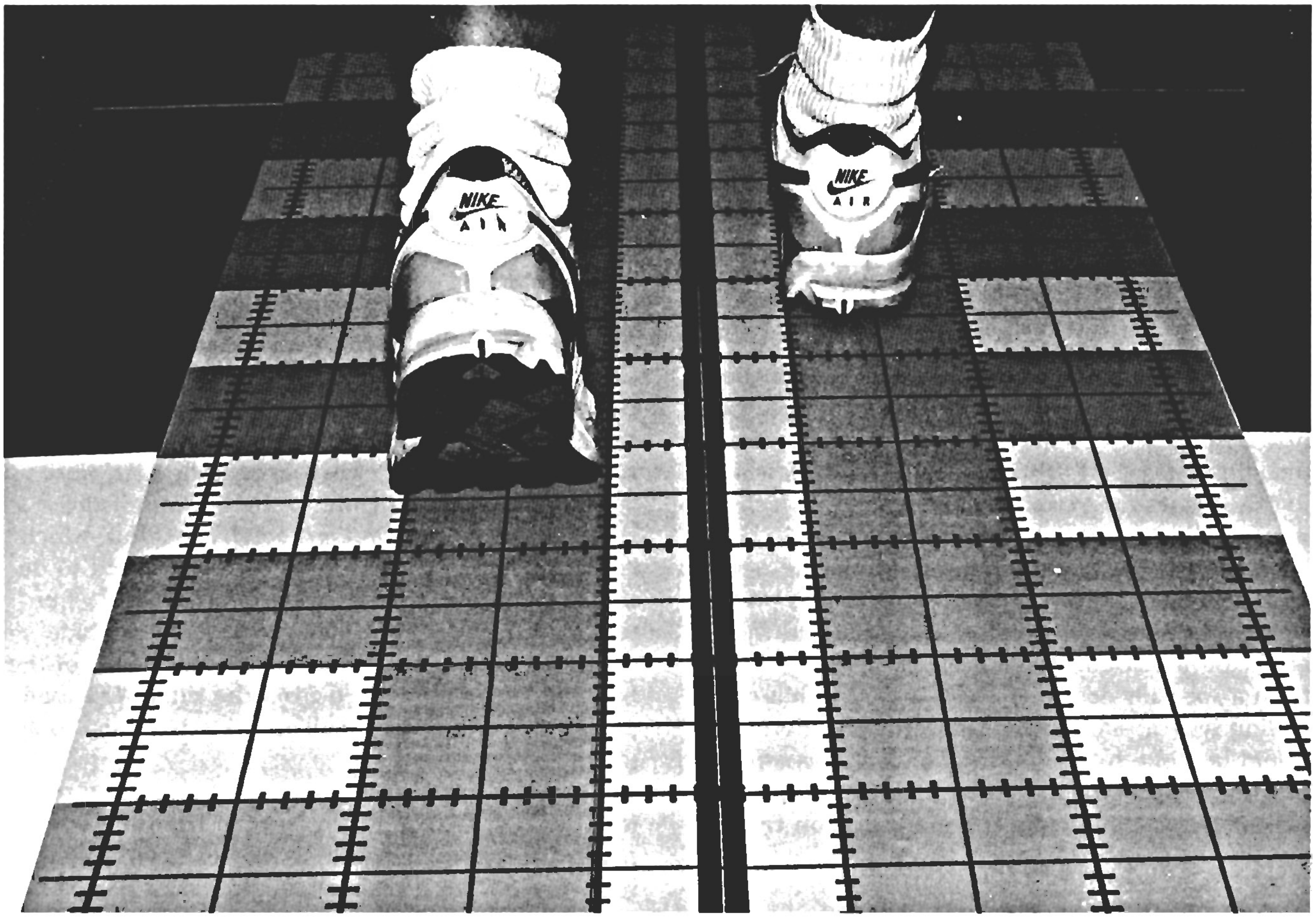

FIGURE 1. Photograph of a subject walking on the grid walkway, viewed from behind. On the heel of the left shoe can be seen the contrasting mark aligned with the arrow-shaped ink pad, attached to the plantar surface of the shoe. The larger squares are 10 cm × 10 cm and have individual centimeter marks on the sides, and each is divided into smaller squares of 5-cm sides. The midline was used as the reference to measure foot placements across the grid, with marks to the left being negative and to the right positive. The color-coding system identifies the meter section of the grid in which the footfall occurred, and can be seen clearly on the right of the grid. The subject is leaving a section indicated by the white edge and entering the section identified with a solid edge. Note that the midpoint of the black section is indicated by a white line, seen in the upper left-hand edge of the picture. Measurements made from this frontal-plane view allow for the determination of step widths.

Two investigators, Rater 1 and Rater 2, who were not involved in determining the foot positions from direct measurements of the ink marks, recorded the positions from the videotapes. Positions along the grid were estimated from the videotape recording taken from the side. The recording taken from behind the subject was used to measure the positions of foot placements on either side of the midline (from which, step width could be determined). The tape was played back in slow motion and paused when the position of the foot could be clearly seen, typically at midstance. The videocassette recorder, used for this purpose, was operated by an independent investigator who used a remote control while the 2 raters estimated the positions of each footfall. There was no communication between the raters during this process. Neither one could see what measurements the other had recorded. The same videotapes were again analyzed, using the same procedure by the same 2 investigators 6 months later, to test for intrarater reliability. The first set of data collected from the videotapes is referred to as trial 1, and the data collected at the later date as trial 2.

Both the direct measurements and video measurements were taken from the positions on the grid where contact was made with the heels. Actual step lengths and step widths were not recorded. Measurements of foot position along the line of progression were made with reference to the start of the walkway, and, therefore, varied from zero to 6 m. Measurements perpendicular to the line of progression were made with reference to the midline of the walkway. Footfalls to the right of the midline were recorded as positive, with footfalls to the left of the midline being negative. The positions of all footfalls made in the central 6 m of the walkway were measured. The number of footfalls for each walk varied with the speed of walking and the functional ability of the subject. In all, there were 224 footfalls, each of which was measured in both the sagittal and frontal planes.

The data collected from the video were plotted against those obtained by direct measurements. Re-

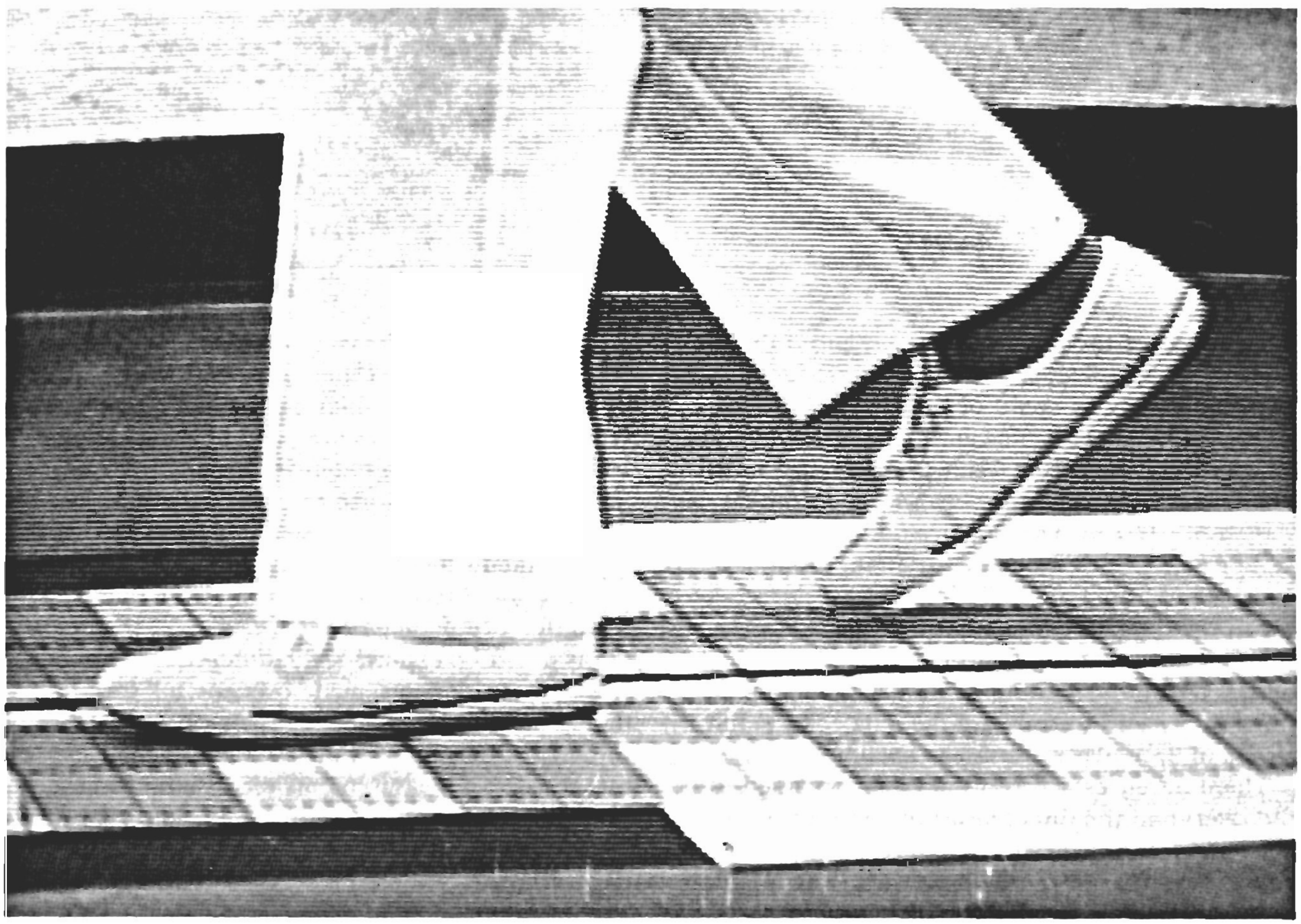

FIGURE 2. Photograph taken from the television monitor shows a subject walking on the grid walkway, viewed from the side. The color-coding system identifies the meter section of the grid in which the footfall occurred, and can be seen clearly at the side of the grid. The heel of the left shoe can be seen making contact where the section indicated by the white edge ends, and the section identified with a solid black edge begins. Measurements made, using this sagittal plane view, allow for the determination of step lengths.

gression equations were obtained from these plots for a straight line of the form $y = c + mx$, where y is the value on the ordinate, x is the value on the absisca, c is the intercept on the ordinate, and m is the slope. Also determined were the coefficients of determination (R^2), which indicate the percentage of variance that is shared by the 2 variables.[4] To determine

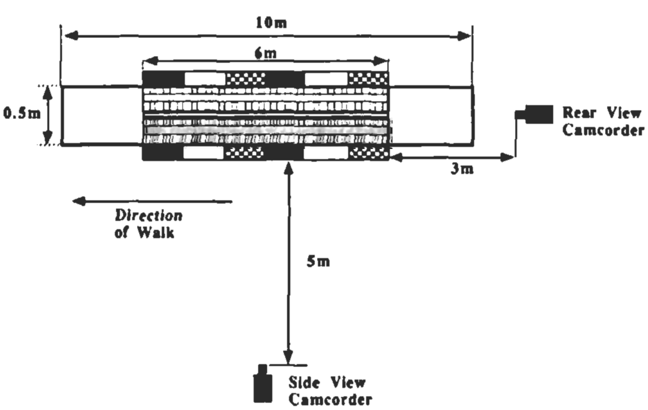

FIGURE 3. A schematic, showing the positions of the camcorders relative to the grid walkway. Note the color-coding along the edges of the walkway, used to identify each meter section of the grid.

how close the data collected by the 2 techniques were, the difference between the direct measurement and that which was determined from viewing the video was calculated for each footfall position. The means of these differences and their 95% confidence intervals were then determined.

RESULTS

The walking speeds and stride times for each of the 3 self-selected walking speeds are shown for the group of nonimpaired subjects and the 2 individuals with gait abnormalities in Table 1. To show the correlation between the 2 techniques, coordinates obtained from direct measurements were plotted against those estimated from video by the 2 raters for both trials and the regression equations determined. Examples of this type of plot are shown in Figures 4 and 5 for both raters for trial 1. The regression equations for all of the comparisons are shown in Table 2. The R^2 values are the coefficients of determination, which all show very high correlations, varying from 0.982 to 1.000. The equations represent a

TABLE 1. Walking speed and stride time for the group of nonimpaired subjects, a patient with Post Polio Syndrome and an elderly woman with compromised balance at each of the 3 self-selected walking speeds. The means and standard deviations are included for the nonimpaired subjects.

	Slow		Medium		Fast	
Group or subject	**Speed (m/s)**	**Stride time (s)**	**Speed (m/s)**	**Stride time (s)**	**Speed (m/s)**	**Stride time (s)**
Nonimpaired (n = 6)	0.78 ± 0.174	1.48 ± 0.186	1.27 ± 0.149	1.08 ± 0.106	1.82 ± 0.106	0.90 ± 0.049
Post polio (n = 1)	0.90	1.21	1.12	1.11	1.71	0.89
Elderly woman (n = 1)	0.33	1.95	0.60	1.37	0.68	1.31

straight line of the form $y = c + mx$ and if the positions measured by the 2 techniques were identical, then the equations would be $y = x$, (ie, the intercept (c) would be at zero and the slope (m) would equal 1). As can be seen from Table 2, the intercepts, if not zero, are very close to zero with a maximum deviation of 0.007 m. The slope values are similarly all close to the perfect value of 1, ranging from 0.974 to 1.005. Thus, there are high positive correlations between the direct measurements and those made from video by both raters. When the same analysis was undertaken to directly compare the data obtained by the 2 raters, and to compare the data collected in trials 1 and 2, similar results were obtained.

The differences between the values obtained by the raters and the direct measurements were calculated. The means of these differences and their 95% confidence intervals were determined, and are shown in Table 3. Ideally, the differences between the direct measurements and each rater's measurements from video should be close to, and distributed about, zero. As can be seen from Table 3, the mean differences are all close to zero and vary from −0.005 to −0.011 for the length measurements made along the walkway, and from 0.001 to 0.0 for the width measurements made across the walkway. For the measurements of foot position across the grid, the 95% confidence intervals are all 0.001 m, reflecting the fact that there was very little variability in the data collected when using the 2 techniques. When the length values are considered, it can be seen that the 95% confidence intervals are a little higher, and, in the worse case, were found to be ±0.012 m. Table 3 also shows the percentages of the measurements that were not different when measured by the 2 techniques, as well as those in which the difference between the 2 was greater than 0.01 m. As might be expected, the differences between length measurements, made over the full length of the walkway, were greater than for the width measurements. In summary, the data in Table 3 show that the direct measurements varied little from those made from video, by both raters, for both trials.

DISCUSSION

The regression equations shown in Table 2 reflect the high degree of correlation between the data obtained by the 2 methods of measurement. This high degree of correlation, together with the very small differences between the measurements made by the 2 techniques, indicate that the new technique, in which the positions of the feet along and across the grid are estimated from video, is as valid as the direct measurement technique.

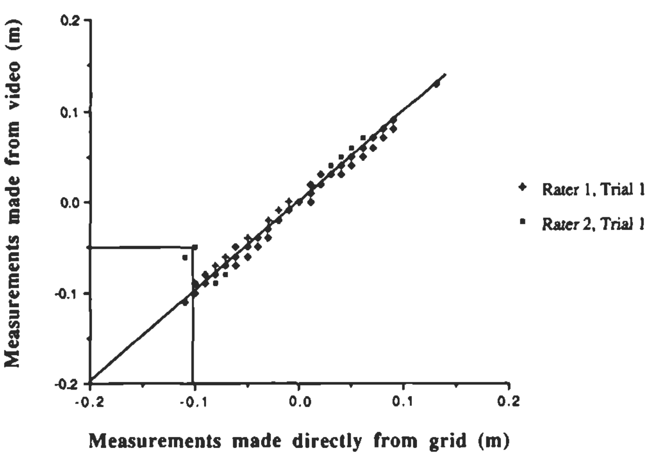

FIGURE 4. Measurements made by rater 1 and by rater 2 on trial 1 from the **frontal plane** (rear view) video plotted against those obtained by direct measurement from the grid. Measurements are for all 224 footfall positions, recorded from all walks by all subjects. The vertical and horizontal lines indicate 1 of the 2 measurements made by rater 2 (from the video) that was 5 cm greater than the direct measurement made (from the grid).

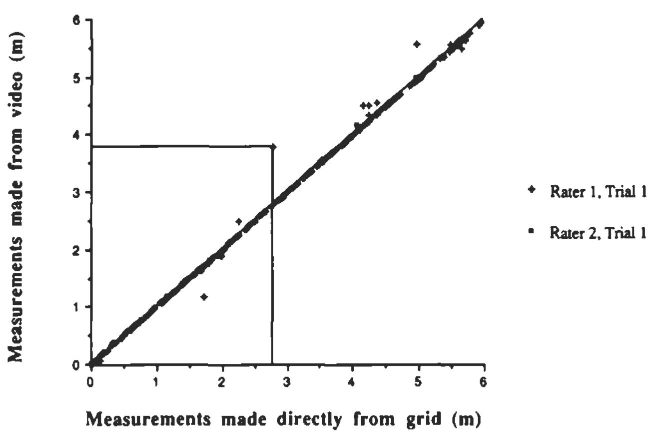

FIGURE 5. Measurements made by rater 1 and by rater 2 on trial 1 from the **sagittal plane** (side view) video, plotted against those obtained by direct measurement from the grid. Measurements are for all 224 footfall positions, recorded from all walks by all subjects. The vertical and horizontal lines indicate the measurement made by rater 1 (from the video) that was 1.0 m greater than the direct measurement made (from the grid).

TABLE 2. Regression equations for measurements made from video by the 2 raters and the direct measurements made from the grid. Thus, in the first equation in the table, D is the measurement made from the grid directly, and R_1 is the measurement made by rater 1 from the video recording.

Direction	Comparison	Regression equation	R^2
Across the grid	Direct vs. rater 1	$D = 0.001 + 1.024R_1$	0.993
	Direct vs. rater 2	$D = 0 + 1.002R_2$	0.983
Along the grid	Direct vs. rater 1	$D = 0.002 + 0.995R_1$	0.997
	Direct vs. rater 2	$D = -0.007 + 1.001R_2$	1.000

D = Direct measurement.
R_1 = Measurement by rater 1 from the video recording.
R_2 = Measurement by rater 2 from the video recording.

The data collected by rater 1 for measurements across the grid were within 1 cm of the direct measurements, as can be seen in Figure 4. However, the data collected by rater 2 included 2 values that were 5 cm different from the value obtained by direct measurement. One of these has been indicated by the vertical and horizontal lines in Figure 4, indicating that the direct measurement was −0.1 m and the measurement obtained by rater 1 was −0.15 m. If one looks at the grid-coloring scheme shown in Figure 1, it is perhaps easy to see how one can mistake the 5-cm mark for the 10-cm mark. However, as seen in Table 3, only a very small percentage of the differences between the 2 methods of measurement differed by more than 1 cm (0.01 m), with the majority of the measurements being the same.

Because the camcorder was centrally mounted, as shown in Figure 3, and panned to keep up with the subject, the data collected from either end of the walkway might be less accurate than data collected from the central region of the walkway. This was not found to be the case as can be seen in Figure 5. All the data were very close to the regression line. Table 3 shows that a smaller percentage of the length measurements were the same for the 2 techniques, than was found for the width measurements. However, in all instances, about 80–90% of the measurements were off by less than 0.01 m. Given that a normal stride length is of the order of 1.3 m, this degree of accuracy is acceptable, but for patients with gait abnormalities, where walking speed is generally slower with shorter stride lengths, the degree of error will be greater. We could find no reference as to what change in stride length is clinically significant; however, walkways designed to measure the spatial parameters of gait electronically have typically been designed with an accuracy of approximately ±1 cm,[2,7,20] similar to that which was found in the videotaping technique in this study. The walkway designed by Robinson and Smidt[15] for clinical use had a resolution of 3 cm. All of these numbers reflect the accuracy for the determination of one measurement. In order to calculate either step length or width, one must calculate the difference between the positions of 2 footfalls, thereby doubling the total error. In the case of our technique, therefore, the accuracy of the step length and step width measurements would be ±2 cm (0.02 m).

When the data collected by the 2 raters were compared to the measurements taken directly from the grid for Trial 1, in the sagittal plane, there are some very noticeable differences for measurements made along the length of the walkway (Figure 5). The most marked difference was 1 m. Rater 1 determined one foot placement to be at 3.8 m along the walkway, when the direct measurement indicated that it should have been at the 2.8 m mark. This aberrant data point has been indicated by the vertical and horizontal lines in Figure 5. The data collected by rater 2 were very close to those obtained by the direct method. This may help explain why the 95% confidence intervals for rater 1, compared to the direct measures, are so much higher than for any of the others in Table 3. These errors in measurements, made along the length of the walkway, were made as a result of misinterpreting the color-coding on the edge of the grid. It should be pointed out that this was only for 2 readings out of a total of 224, and that similar errors did not show up in trial 2. These errors would almost certainly have been detected

TECHNICAL NOTE

TABLE 3. Means and 95% confidence intervals for the differences between the measurements made directly from the grid and those made by the 2 raters from video recording in both trials. All comparisons are based on data collected from all 224 footfall positions, recorded from all walks made by all subjects.

Direction	Comparison	Mean ± SD	95% Confidence interval		Difference (%)*	
			Lower	Upper	None	>0.01 m
Across the grid	Trial 1 direct vs. rater 1	0.001 ± 0.005	0.001	0.002	74.0	0
	Trial 1 direct vs. rater 2	0 ± 0.007	−0.001	0.001	76.7	1.3
	Trial 2 direct vs. rater 1	0.001 ± 0.006	0.001	0.003	68.3	0.9
	Trial 2 direct vs. rater 2	0.001 ± 0.005	0	0.001	74.6	0.9
Along the grid	Trial 1 direct vs. rater 1	−0.011 ± 0.094	−0.024	−0.001	37.1	20.1
	Trial 1 direct vs. rater 2	−0.005 ± 0.014	−0.007	−0.003	48.2	13.8
	Trial 2 direct vs. rater 1	−0.005 ± 0.04	−0.01	0.001	42.2	15.1
	Trial 2 direct vs. rater 2	−0.002 ± 0.014	−0.004	−0.001	45.6	10.2

* The percentage of measurements in which there was no difference between the direct method and the rater and the percentage of measurements in which the difference between the 2 methods was greater than 0.01 m.

and corrected had the actual step lengths been calculated from these measurements since obvious asymmetries for these steps would result.

The grid used in our study was designed to make the reading of these positions easier by including a color-coding system to identify various sections of the walkway. Since Gaudet et al[6] obtained similar results using a different grid, one may extrapolate the use of the technique with other grids of known dimensions. Thus, in a clinic, this technique might well be adapted using floor tiles of known size; however, the larger the size of the tile, the less accurate the estimations will be. If tiles are used, then one might consider applying a color-coding system similar to the one used in this study in order to make identification of positions simpler.

It has been shown that the temporal variables of gait may be accurately and reliably obtained from a video recording and a multimemory stopwatch.[21] It was thought that if one could also measure spatial gait variables from the same recording, then a more comprehensive gait assessment would result. This is what prompted our study. Temporal variables can be collected using the mouse button to directly input the data into the computer, and thereby eliminate the need to collect the data with a stopwatch.[19] The computer can then record the data and calculate the results. A similar approach is being taken to measure the spatial variables; however, for making these measurements, a video recording will be a prerequisite. The other major benefit of using video is that a permanent record of the patient walking is made and can be reviewed at any time, not simply used to determine the spatial variables, as was done in this study. Thus the video can assist with subjective assessment and provide visual feedback to the patient. The major disadvantage of the video system is the cost. In our study, 2 camcorders were required in order to determine the positions along and across the grid. This set-up also required 2 people to operate the camcorders. In some clinics, there may also be legal issues that preclude videotaping patients.

From a pragmatic point of view, it may be quicker, easier, and cheaper to use the direct measurement technique and not be concerned with videotaping the subjects as was done in our study. Because we wanted to estimate the positions of the foot from video, rather than the positions of the ink marks left on the grid, we used stamp pads, hidden from view. However, for normal use in our laboratory, we have developed a simpler method for measuring the positions of footfalls directly from the grid, based on a modification of the technique proposed by Cerny.[1] The marker pen is first passed through a small block of foam rubber, which is then attached to the heel of the foot or shoe with adhesive tape. This minor modification allows the height of the pen to be easily adjusted so that the pen leaves a small point of ink, indicating the position of heel contact. Two different colored pens are used to distinguish left from right. Once the pens are attached and their heights adjusted, the subject walks along the grid. The positions of the ink marks are determined from the grid and recorded on a datasheet. It is important to use ink that can be easily erased so that the marks can be wiped from the grid before the next walk.

With certain gait patterns, the technique may have to be modified. For example, for a patient that has a step length less than their shoe length, the position of the heel of the far foot will not be visible at initial contact. In such a case, one could make measurements with respect to the front of the foot or wait until midstance on that foot, at which point the foot closer to the camera will have moved forward, revealing the position of the heel to be measured. Likewise, the position of the heel at initial contact, when viewed from behind, will be hidden in patients who have a hip-adduction abnormality, and again, one would have to determine the position after the rear foot has entered the swing phase. The basic principle here is that the grid is a 2-dimensional ruler, and to determine the spatial gait variables one must be able to see the positions of the anatomical landmarks that define those variables on the grid. In the cases where this is not possible, the video technique will be inappropriate and one could place ink markers on the heels of the subjects to determine the positions of the foot contacts from measurements made directly from the grid. Similarly, in order to take the measurements from the grid, the subject must remain within the confines of the grid. Thus, for some neurological conditions such as ataxias, or for young children that wander, neither the video technique nor the ink markers would lend themselves to obtaining the measurements from the grid. Only further clinical studies on a variety of gait abnormalities will answer these concerns.

CONCLUSION

The grid used in this study is a useful tool for quickly determining the positions of foot placements during gait. This study demonstrates that accurate and reliable estimates of foot position can be made from a video recording of a subject walking across a grid of known dimensions. Even without the use of a video system, the grid greatly simplifies the determination of the positions of foot placements made by marks left on the grid, using pens attached to the foot or shoe.

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