Kar. Univ. J. Sc. 24(2) 7-18 (1996)

GAIT ANALYSIS USING MOIRE FRINGE TOPOGRAPHY AND RASTERSTEREOGRAPHY (SIMULTANEOUS RECORDING)

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ABSTRACT

Moiré fringe topography and rasterstereography are noninvasive 3-D optical imaging techniques. They provide height and curvature maps of three-dimensional objects respectively. In gait analysis and other movement activities the same position cannot be reproduced again. It is desired to record heights and curvatures of human trunk (e.g. selected points on human back) at the same time. A technique for simultaneous moiré and raster recording is introduced using selective filtering.

Keywords: Moiré fringe topography, rasterstereography, motion analysis, optical filtering

INTRODUCTION

Throughout the course of history, man has performed measurements by eye estimate, tape, and calipers to describe the form of the human body. Over 4000 years ago Egyptian artists set up a system of measurement based on the width of a human hand.

The need to find a convenient three-dimensional measuring system led to the development of photogrammetry in the middle nineteenth century. Medical photogrammetry is the term used to cover all applications of photogrammetry in the broad field of medicine. These include stereophotogrammetry, holography, integrated surface imaging system (ISIS), 3-D video laser scanning system, moiré fringe topography and rasterstereography.

We are in need of methods which are inexpensive, easy to implement, simple to be performed by moderately trained personnel and elegant enough to permit handling by various algorithms. Moiré fringe topography and rasterstereography have all these characteristics. The first one provides height maps and the second one curvature maps. If we are able to record and process information from both these techniques we may obtain a complete profile of human trunk during every cycle of gait. Such information may be used in modeling of human gait and understanding of various neurological disorders.

Moiré Fringe Topography

Moiré fringes are a series of interference fringes arising from the superposition of sets of parallel lines or threads, the sets being slightly inclined to one another. Width of the lines of the grid should be equal to the space between them. The shadow type moiré topography apparatus used in the

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pitch of the projected grid matched with the pitch of the deformed grid. Formulae to calculate the distances are listed in appendix-A.

Rasterstereography

Rasterstereography is very similar to stereophotography. The difference is that one of the cameras is replaced by a slide projector and a raster (Fig. 3*b*) is projected on the body. Because of the curvature of the body the raster is distorted. Study of this distortion provides information about the topological properties of the surface under study (Hierholzer & Frobin, 1981). The remarkable feature of rasterstereography is that it does not require a specific arrangement of the apparatus to obtain meaningful rasters, whereas only a specific geometry of the moiré set up would provide contours with desired mathematical properties.

Consider a raster projected on a cylindrical surface. Let us take x and z axes parallel to each set of parallel lines (grids) of raster pattern. Let the cylinder be aligned in such a way that its axis coincides with the z axis. Using cylindrical coordinates (ρ,ϕ,z) let us describe the cylinder as the volume enclosed by intersection of the surfaces $\rho = \rho_0$, $z = 0$, $z = z_0$. Note that the curved surface of the cylinder has two curvatures at every point. The curvature corresponding to the curve defined by intersection of the surfaces $\rho = \rho_0$, $z = z_1$, $(0 \le z_1 \le z_0)$ is $\kappa_1 = 1/\rho_0$, whereas the curvature corresponding to the line defined by the intersection of $\rho = \rho_0$, $\phi = \phi_0$ $(0 \le \phi_0 < 2\pi)$ is $\kappa_2 = 0$. The raster pattern projected on this cylinder shall be distorted. The lines parallel to z axis shall appear straight but their spacing shall not be uniform. From the variation of their spacing magnitude of κ_1 may be determined. To determine whether the surface is convex (positive curvature) or concave (negative curvature) one notes whether the spacing is increasing or decreasing towards the edges. If the surface is convex (concave) the spacing shall decrease (increase) when one moves away from the region under consideration. Further, the grids parallel to x axis shall converge (diverge) on moving away if the surface is positively (negatively) curved. A similar procedure applied to the other set of grids would give the local value of κ_2. These simple ideas could be generalized for surfaces having other type of curvatures.

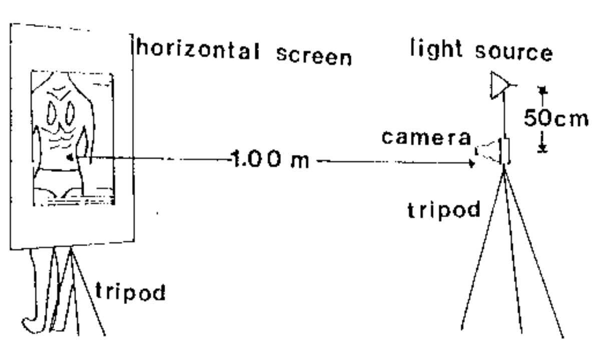


Fig. 1. Set-up for shadow type moiré fringe topography

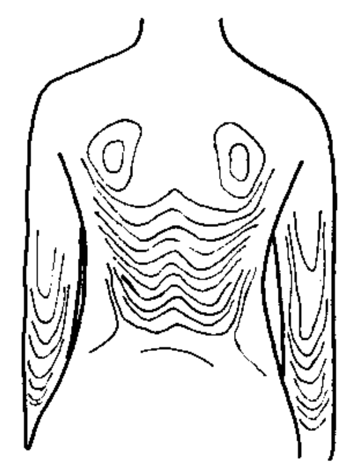


Fig. 2. Moiré pattern of a normal spine

Therefore, we see that using a raster grid we may determine the curvatures κ_1 and κ_2 at amy point. If curvatures at more than a few points are needed (e.g. curvature maps of the human trunk) algorithms must be developed to determine the curvatures from digitized data. Computing time may be minimized by using multigrid techniques. Where the variation of curvature is small a coarse grid may be used. For larger curvature variations a finer grid may be used (Stüben, 1992). Formulae to calculate curvatures from a rasterstereograph are listed in Appendix B.

THE HUMAN GAIT

The bipedal locomotion is in some ways the simplest and at the same time the most difficult form of locomotion to control. The simplicity arises from the fact that the legs are activated out of phase with one another in each step, as in walking.

The complexity of bipedal locomotion arises from the relatively unstable equilibrium that occurs, even when standing on two legs. This state is like an inverted pendulum. In a normal pendulum a displacement in either direction from its lowest point will produce a gravitational force that tends to restore the pendulum to this point. If the pendulum is inverted displacement of the weight from its highest point will produce a net gravitational force that will tend to displace the weight further. The feet provide a narrow base of support for the body's center of mass. Small displacements forward or backward can be compensated by the reflexes activated, for example, by stretching the ankle extensors or flexors. Appendix E explains the anatomical terms used in this discussion.

Once the body's center of mass has moved beyond the base of support provided by the feet the body shall fall forward (or backward) unless one limb is moved to provide a broader base of support in which the center of mass lies between the two feet. Walking is initiated by allowing the body to fall forward (generally by inhibiting activity in ankle extensors) to an unstable position and then moving one leg forward to re-establish equilibrium. Each step may, therefore, be considered as an unstable fall, followed by a return to a stable posture. In normal gait each limb alternately returns the body to stability. Steps involved in the gait of a normal person are shown in Fig. 4 and listed in Appendix C.

Normal gait of a human being is always in the sagittal plane. The flexing and extending of the arms and legs, which causes the body to move, also occurs in the same plane. Normal gait is thus a combination of *flexion* and *extension*.

3-D Optical Imaging in Gait Analysis

Moiré fringe topography is being widely applied in the detection (Adair, van Wijk & Armstrong, 1977), documentation (Willner, 1979), quantification (Kamal, 1983; 1987; 1996*a*,*b*) and follow-up (Kamal & Lindseth, 1980) of spinal deformities especially scoliosis (lateral curvature of the spinal column). It has also been used for the study of chest wall deformities (Shochat & Csongradi, 1983) as well as anthropometry (Windischbauer, 1983). Currently moiré topographs are also used to keep permanent records of patients suffering from rheumatic disorders as well as low back pain. Rasterstereography is also being applied selectively to monitor curvature of spinal column especially in scoliosis and kyphosis (Hierholzer & Frobin, 1981).

One of the areas in which moiré fringe topography and rasterstereography could be extremely useful is the study of gait. Preliminary studies of posture (Suzuki, Yamashita, Yamaguchi & Armstrong, 1981) and gait in normal subjects (Moreland & Lewis, 1981) and polio patients (Siddiqui & Choudhry, 1990) have already been performed. A study of posture and gait of patients suffering from neurological disorders, e. g. cerebral palsy would provide valuable insights into the mechanism of these disorders. Moiré and raster studies could also be supplemented by other techniques like edge- and intensity-based algorithms etc.

Movement on treadmill is not identical to natural, unhindered movement. For an understanding of gait pattern, natural walking must be studied. However, in natural walking distance of the subject from the camera and the slide projector will not be constant. Therefore, in order to obtain sharp pictures proper focusing should be achieved. This could be done manually or electronically using feedback mechanism.

To establish the feasibility of using moiré fringe topography and rasterstereography in gait analysis and to suggest means to devise a preliminary analytical description of children's gait in the age group 8 to 12 years old we conducted the following study (Siddiqui & Choudhry, 1990):

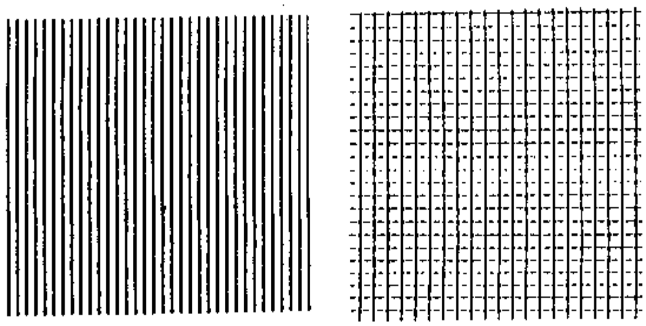
Apparatus. The apparatus used in the study is listed in Appendix D. In addition to the standard optical components the following were developed in our laboratory for the purpose of this study.

A *fine adjustment device* was used which was a plane sheet of cardboard mounted on a mechanical device similar to traveling microscope arrangement so that it could be moved over small distances. Moiré and raster grids were sharply focused on this plane. This was used as the reference plane in the rest of the photographing session. It was much easier to focus a subject walking on treadmill.

A *conic reference device* was constructed which was a right-circular cone. Dimensions of the cone (its depth as a function of height) were known. Moiré fringes formed on the cone can be used to calibrate the fringe pattern obtained during the gait cycle, because during normal walking it will not be possible to keep track of the distance of the subject from the camera which is essential to theoretically calculate the depth by counting the moiré fringes.

Location. The studies were conducted in Orthopaedic and Medical Institute as well as Bashir Hospital both located in Karachi.

The Work. A slide projector was placed at one end of a dark room and a healthy boy of age 9 years was asked to walk normally in its light. We projected a moiré grid (Fig. 3*a*) from a slide projector on the child's back and photographed the back using a 35 mm camera. Distance between the subject and the camera ranged between 324 & 395 cm. Camera was placed at a distance of 70 cm from the projector so that it directly faced the child. The line joining the camera lens and the projector lens must always be parallel to the frontal plane whenever moiré grid is projected. The procedure was repeated with a raster grid (Fig. 3*b*) placed in the slide projector. The fine adjustment device also acted as reference plane for rasterstereography. The camera was mounted on a tripod to avoid hand movements. As the boy walked, his photographs were taken at a rate of 5 frames per second with the help of a built-in automatic motor in the camera. A total of 4 film rolls of 36 exposures were used. Out of about 150 photographs obtained 8 snaps were studied giving the front and back view of the boy and showing the stances listed in Appendix E. Similar photographs were then taken of two female polio patients of ages 9 and 12 years respectively.



a b

Fig. 3. Grids for (*a*) moiré fringe topography and (*b*) rastestereography

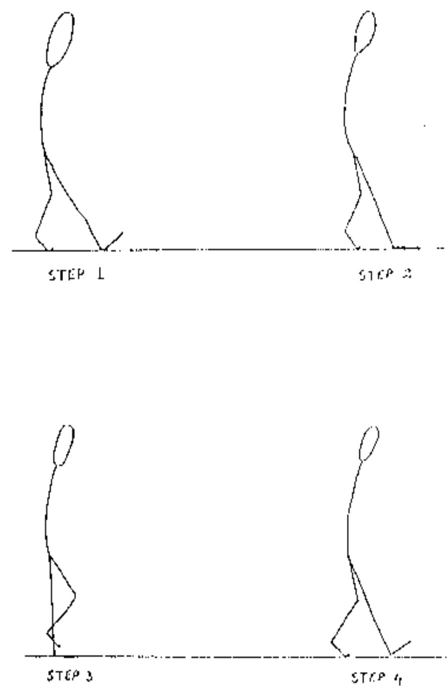


Fig. 4. Four phases of a single step.

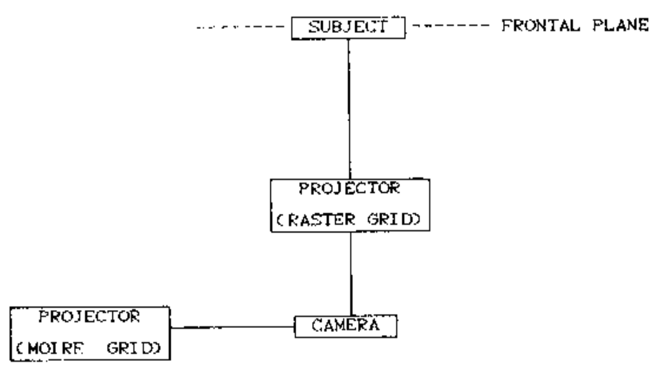


Fig. 5. Layout for simultaneous moiré and raster recording.

Simultaneous Moiré and Raster Recording

A separate record using moiré fringe topography and rasterstereography for gait analysis is not of much use, because we are getting curvatures during one walking sequence and heights during the other walking sequence. A simultaneous recording with on-line data acquisition and processing capability is required if we want to model trunk asymmetries during movement

For simultaneous moiré and raster recording we use a 35 mm camera, 2 slide projectors, a moiré grid and a raster grid. Moiré grid is prepared in red color and raster grid prepared in blue color. Both the grids are simultaneously projected on the body using the two slide projectors which are placed as given in the layout of Fig. 5. After a color photograph was obtained a red filter matching with the color of the original moiré grid was placed on it[3]. The red moiré grids became invisible and the blue raster grids appeared black. This was then fed in the scanner for analysis using rasterstereography algorithms. Similarly a blue filter matching with the color of the raster grid was placed on the picture. Raster was suppressed and the moiré grid appeared black. Then a standard black moiré grid was projected at the same angle to produce moiré fringes. Success of this procedure depends critically on proper matching of the colors.

DISCUSSION AND CONCLUSION

Moiré and raster techniques offer much scope in medical sciences. In the coming years they will supplement and possibly decrease the conventional X rays. The recent development of a procedure to obtain reproducible moiré pictures (Kamal, 1990; Kamal, Benoni & Willner, 1994) will increase the potential usefulness of this technique in the follow-up of spinal deformities as well as neurological disorders. Noninvasive 3-D optical techniques may find applications in the study of gait and movement analysis especially analysis of gymnastic performance. Moiré examination of spine may be useful in screening potential gymnasts and athletes (Akram & Kamal, 1991). There is a need to bring clinically relevant information which may provide diagnostic clues to the surgeon without taking the trouble to interpret the patterns or the results. For example, an algorithm which calculates and displays height asymmetries about the sagittal plane from moiré topographs and curvature asymmetries from rasterstereographs may be useful in screening and follow-up of scoliosis patients.

ACKNOWLEDGEMENTS

The authors would like to thank Mr. Salman Tahir who helped us with his great skill of photography. On the clinical side we received help from Dr. Raza Ali, Orthopedic Surgeon (A. O. Clinic, Karachi), Dr. Bashir A. Khan, Consultant Orthopedic Surgeon (Abbasi Shaheed Hospital, Karachi), Dr. Rahim, Orthopedic Surgeon, Dr. Sarwar, R. M. O. (Orthopedic & Medical Institute, Karachi). Last but not least we are indebted to our fellow members of Biomedical Physics Research Group, Bashir Ahmad and Umar F. Hashmi who were working on related projects (cf. Ahmad & Hashmi, 1990) and hence provided opportunity for interaction and critical evaluation of our work at every stage of the project.

APPENDIX A. Formulae for Height from Moiré Fringe Separation

a. For shadow type moiré apparatus the distance h_n from the n^{th} fringe to screen (the highest elevation must touch the screen) may be found from (Takasaki, 1974):

(A.1) $$h_n = n\,\lambda\,[(d/s_0) - n]^{-1}$$

where λ = distance between the camera and the screen

d = distance between the camera and the light source

s_0 = screen interval (line thickness plus spacing)

[3] The idea of matching filters was suggested by ASC.

b. From the above the height difference between successive fringes in a shadow type apparatus may be calculated as (Kamal & Lindseth, 1980):

(A.2) $\Delta h = \lambda\,(d/s_0)\,[(d/s_0) - (n+1)]^{-1}\,[(d/s_0) - n]^{-1}$

For U. S. A. studies (1980-82), we had $\lambda = 100$ cm, $s_0 = 1.0$ mm, $d = 50$ cm, which gave $\Delta h = 0.20$ cm for $n = 1$. For Karachi studies (1988-89), the parameters were $\lambda = 150$ cm, $s_0 = 1.4$ mm, $d = 110$ cm, which gave $\Delta h = 0.19$ cm for $n = 1$.

c. For the grating hologram type system developed by our group in Karachi the distance H_n from the n^{th} fringe as compared to the highest elevation is given by:

(A.3) $H_n = nM\,(M + 1)\,fP_0\,(L - nMP_0)^{-1}$

where
- M = magnification of the moiré grid
- f = focal length of the projector lens
- P_0 = moiré grid interval (line thickness plus spacing)
- L = distance between the camera and the projector lens

The above formula may be obtained by adapting the derivation of Suzuki, Yamashita, Yamaguchi & Armstrong (1981) for our system.

d. The height difference between successive fringes for our grating hologram system, therefore, may be expressed as:

(A.4) $\Delta H = M\,(M + 1)\,f\,(P_0/L)\,[1 - (n + 1)MP_0/L]^{-1}\,[1 - nMP_0/L]^{-1}$

retaining only the linear term in P_0/L ($P_0 \ll L$). We had $L = 70$ cm $P_0 = 0.0242$ cm, $M = 18.15$, $f = 8.5$ cm, which gave $\Delta H = 1.04$ cm. The sensitivity may be increased by using finer grid (decreasing P_0), and using a lens of shorter focal length. Increasing L may produce distortions.

APPENDIX B. Formulae for Curvature Computation from Rasterstereographs

Let us suppose that a given raster grid on a plane surface (reference surface) has a periodic spacing equal to s. On the curved surface the spacing appears to be d. Let the portion of the curved surface under study may be the part of a great circle of radius ρ. Now, we have $s = \rho\phi$, where ϕ is the angle subtended by arc of length s. Therefore

(B.1) $\phi = s(1/\rho) = \kappa s$

Also

(B.2) $d = \rho \sin\phi = \rho\,[\phi - (1/3!)\phi^3 + (1/5!)\phi^5 - ..] = s\,[1 - (1/3!)\kappa^2 s^2 + (1/5!)\kappa^4 s^4 - ..]$

Since ϕ is small we neglect fourth and higher powers. Therefore

(B.3) $d/s = 1 - (1/3!)\kappa^2 s^2$

which may be put in the form

(B.4) $\kappa = \pm (1/s) [6(1 - d/s)]^{1/2}$

If $d = s$, $\kappa = 0$ and we have the condition of a flat surface.

APPENDIX C. Steps of Normal Gait

	Right Leg		*Left Leg*
Step 1	Right leg forward, left toe and right heel touching the ground. Center of gravity lying between the two feet.		
Hip	Extension	*Hip*	Extension
Knee	Extension	*Knee*	Extension
Ankle	Dorsiflexion	*Ankle*	Planter Flexion
Step 2	Right leg forward, right toe and right heel (that is, the right foot) and the left toe on the ground.		
Hip	Extension	*Hip*	Extension
Knee	Flexion	*Knee*	Flexion
Ankle	Neutral	*Ankle*	Neutral
Step 3	Left foot in the air (moving forward), body supported by right foot only. Center of gravity lying on top of right foot.		
Hip	Flexion	*Hip*	Flexion
Knee	Flexion	*Knee*	Flexion
Ankle	Neutral	*Ankle*	Neutral
Step 4	Left leg forward, right toe and left heel touching the ground. Center of gravity lying between the two feet		
Hip	Extension	*Hip*	Extension
Knee	Extension	*Knee*	Extension
Ankle	Planter Flexion	*Ankle*	Dorsiflexion

APPENDIX D. Apparatus Used in the Study

Apparatus	*Specifications*
Camera	NIKON MODEL EM (body only)
Zoom Lens	NIKKOR-F
	Focal length 50-135 mm (1:3.5)
Film Rolls	a) KODAK TMAX, ASA 400, B&W
	b) KODAK TMAX, ASA 3200, B&W
Projector	Make GRIFFIN & GEORGE (UK)
	Lamp 24 V, 150 W, TUNGSTEN HALOGEN 1.9 AMPS
	Lens 85 mm
Video Camera	National, Model M5
Fine Adjustment Device	(described in the text)
Conic Reference Device	(described in the text)

APPENDIX E. Anatomical Terms

I. Directional Terms

Superior: A *is superior to* B means A is nearer to the head than B.

Inferior: B *is inferior to* A means A is superior to B.

Medial: B *is medial to* A means B is closer to the midline than A.

Lateral: A *is lateral to* B means B is medial to A.

Proximal: C *is proximal to* D means C is nearer to attachment point of a limb than D.

Distal: D *is distal to* C means C is proximal to D.

Anterior: *Anterior point* is a point which is nearer to or in front of the body.

Posterior: *Posterior point* is a point which is nearer to or at the back of the body.

The above terms are relative.They are used to compare any two arbitrary points on the body.

II. Cardinal Planes

Sagittal: Vertical plane dividing the body into left and right portions.

Frontal: Vertical plane dividing the body into anterior and posterior parts.

Transverse: Horizontal plane dividing the body into superior and inferior parts.

These planes remain the same regardless of body orientation with respect to earth.

III. Anatomical Axes

Transverse: Normal to sagittal plane through the body from side to side.

Longitudinal: Normal to transverse plane through the body from top to bottom.

Anteroposterior: Normal to frontal plane through the body from front to back.

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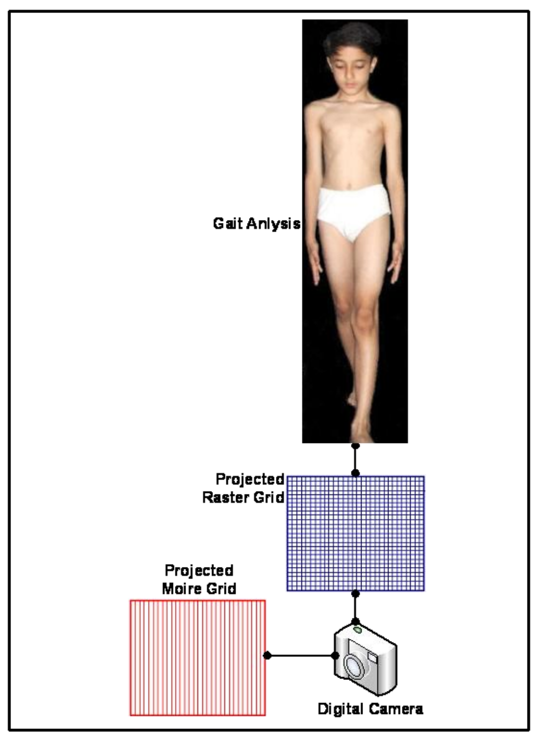
ADDITIONAL NOTES *(related to this paper, but not part of the published manuscript)*

Correction on page 15 — Appendix C: Steps of Normal Gait

***Step 2*:** Right leg forward, right toe and right heel (that is, the right foot) *touching the ground* as well as the left toe on the ground.

Normal gait should be studied using moiré fringe topography, rasterstereography and video-recording with the child attired solely in white, exercise (gym) briefs (which are form fitting), barefoot, stripped to waist — see figure on right. A much-clearer diagram of the concepts elaborated in Fig. 3 and 5, which appears in the document: *3-D-spinal-column-surface analysis (height and curvature maps) by combining moiré fringe topography and rasterstereography with backscatter-X-ray-scanning technology*, reproduced on the extreme right from the following link: http://www.ngds-ku.org/Presentations/Backscatter.pdf



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