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Ground reaction forces, kinematics, and muscle activations during the windmill softball pitch

GRETCHEN D. OLIVER & HILLARY PLUMMER

Health Science, Kinesiology, Recreation and Dance, College of Education and Health Professions, University of Arkansas, Fayetteville, Arkansas, USA

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Abstract

The aims of the present study were to examine quantitatively ground reaction forces, kinematics, and muscle activations during the windmill softball pitch, and to determine relationships between knee valgus and muscle activations, ball velocity and muscle activation as well as ball velocity and ground reaction forces. It was hypothesized that there would be an inverse relationship between degree of knee valgus and muscle activation, a direct relationship between ground reaction forces and ball velocity, and non-stride leg muscle activations and ball velocity. Ten female windmill softball pitchers (age 17.6 ± 3.47 years, stature 1.67 ± 0.07 m, weight 67.4 ± 12.2 kg) participated. Dependent variables were ball velocity, surface electromyographic (sEMG), kinematic, and kinetic data while the participant was the independent variable. Stride foot contact reported peak vertical forces of 179% body weight. There were positive relationships between ball velocity and ground reaction force ($r = 0.758$, $n = 10$, $P = 0.029$) as well as ball velocity and non-stride leg gluteus maximus ($r = 0.851$, $n = 10$, $P = 0.007$) and medius ($r = 0.760$, $n = 10$, $P = 0.029$) muscle activity, while there was no notable relationship between knee valgus and muscle activation. As the windmill softball pitcher increased ball velocity, her vertical ground reaction forces also increased. Proper conditioning of the lumbopelvic–hip complex, including the gluteals, is essential for injury prevention. From the data presented, it is evident that bilateral strength and conditioning of the gluteal muscle group is salient in the windmill softball pitch as an attempt to decrease incidence of injury.

Keywords: *Electromyography, injury implications, lower extremity, motion analysis*

Introduction

The sport of fast-pitch softball has become very popular for female athletes and is a unique athletic skill that is beginning to be explored (Barrentine, Fleisig, Whiteside, Escamilla, & Andrews, 1998; Guido, Werner, & Meister, 2009; Oliver, Dwelly, & Kwon, 2010; Rojas et al., 2009; Werner et al., 2005; Werner, Jones, Guido, & Brunet, 2006). It has been reported that during 2003 more than 2 million girls participated in the sport of softball (Werner et al., 2005). Despite its popularity, there is limited research regarding the sport of softball. It has been reported that the windmill softball pitch has sequential activation of proximal-to-distal segmental motions of the trunk, shoulder, elbow, and wrist, respectively (Oliver et al., 2010). Alterations in this sequential motion could result not only in decreases in ball velocity (Oliver et al., 2010) but, more importantly, an increased potential for injury (Kibler, 1998; Kibler & Sciascia, 2006; McMullen & Uhl, 2000).

Habitual motor patterns of the upper extremity are dependent upon lower extremity and torso muscle activation prior to any upper extremity muscle activation (Zattara & Bouisset, 1998). Thus, based on the premise that the lower extremity drives the upper extremity, it should be assumed that the activation of the gluteal muscle group controlling the pelvis would essentially control the upper extremity. During the baseball pitch, the proximal segments of the lower extremity and torso work succinctly and sequentially to accelerate the upper extremity for optimal force production (Pappas, Zawacki, & Sullivan, 1985). Although the baseball pitching motion is overhand in nature, versus the windmill softball pitch which is underhand in nature, the sequentiality of segments in an attempt to generate ball velocity is similar (Putnam, 1991, 1993).

All upper extremity movement follows a proximal-to-distal neuromuscular pattern (McMullen & Uhl, 2000). Upper extremity motion occurs only after

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Correspondence: G. D. Oliver, Health Science, Kinesiology, Recreation and Dance, College of Education and Health Professions, University of Arkansas, 326B HPER Building, Fayetteville, AR 72701, USA. E-mail: goliver@uark.edu

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synergistic neuromuscular activations of the lower extremity and torso (Bouisset & Zattara, 1981; Zattara & Bouisset, 1998). Previously, ground reaction forces have been examined in softball pitching because of the importance of the lower extremity throughout the pitching motion (Guido et al., 2009; Werner et al., 2005). It has been reported that ground reaction forces in youth windmill softball pitchers during stride foot contact are generated anteriorly, medially, and vertically in an attempt to break the forward momentum of the body and provide a base of support for trunk rotation and ball release.

With the increased ground reaction forces during stride foot contact of the windmill softball pitch, the lower extremity kinematics and muscle activations are of interest. Proper transfer of ground reaction forces, from the lower extremity, up the kinetic chain is essential in the prevention of injury (Kibler, 1998; Kibler & Sciascia, 2006; McMullen & Uhl, 2000). Lower extremity injuries commonly suffered by fastpitch softball pitchers are often overuse in nature and affect the knee and lower leg (Hill, Humphries, Weidner, & Newton, 2004; Loosli, Requa, Garrick, & Hanley, 1992). No research to date has described ground reaction forces, lower extremity kinematics, and muscle activations during the windmill softball pitch. Thus, the aims of the present study were to examine quantitatively ground reaction forces, kinematics, and muscle activations from stride foot contact to ball release during the windmill softball pitch, and to determine relationships between knee valgus and muscle activations, ball velocity and muscle activation as well as ball velocity and ground reaction forces. It was hypothesized that there would be an inverse relationship between degree of knee valgus and muscle activation just as there would be a direct relationship between ground reaction forces and ball velocity, and non-stride leg muscle activations and ball velocity.

Methods

Study design

A controlled laboratory design was implemented in the current study. The independent variable was the participant while the dependent variables were ball velocity, sEMG kinematics, and kinetics. Ten female windmill softball pitchers (age 17.6 ± 3.47 years, stature 1.70 ± 0.07 m, weight 67.4 ± 12.2 kg) volunteered to participate. All participants had recently finished their competitive spring softball seasons, and were deemed appropriately conditioned for participation. Additional criteria for participant selection included coaching staff recommendation, multiple years (up through the current season) of pitching experience, and freedom from injury throughout the recently completed competitive softball season. Throwing arm dominance was not a factor contributing to participant selection or exclusion for this study. All test protocols used in the current study received approval from the University's Institutional Review Board, and prior to participation the approved procedures, risks, and benefits were explained to all participants. Informed consent was obtained from the participants, and the rights of the participants were protected according to the guidelines of the University's Institutional Review Board.

Participants reported for testing before engaging in resistance training or any vigorous activity that day. The locations of bilateral gluteus maximus and medius were identified through palpation. Before testing, the identified locations for surface electrode placement were shaved, abraded, and cleaned using standard medical alcohol swabs. Subsequent to surface preparation, adhesive 3M Red-Dot bipolar (Al/AgCl) disk surface electrodes, 6 cm in diameter (3M, St. Paul, MN) were attached over the muscle bellies and positioned parallel to muscle fibres using techniques described by Basmajian and Deluca (1985). Once all electrodes had been secured, manual muscle tests were conducted using techniques described by Kendall and colleagues (Kendall, McCreary, Provance, Rodgers, & Romani, 1993). Manual muscle testing was conducted to establish baseline readings for each participant's maximum voluntary isometric contraction (MVIC) to which all surface electromyographic (sEMG) data could be compared.

Surface electromyographic data were transmitted to the MotionMonitor$^{\mathrm{TM}}$ motion capture system (Innovative Sports Training Inc., Chicago, IL) through a Noraxon Myopac 1400L 8-channel amplifier. The signal was full-wave rectified and smoothed based on the smoothing algorithms of root mean square at windows of 100 ms. Throughout all testing, the sEMG data were sampled at a rate of 1000 Hz. All sEMG data were notch filtered at frequencies of 59.5 Hz and 60.5 Hz respectively (Blackburn & Pauda, 2009).

In addition to sEMG data, kinematic and kinetic data were collected using the MotionMonitor$^{\mathrm{TM}}$ motion capture system (Innovative Sports Training Inc., Chicago, IL). Before completing test trials, participants had a series of 10 electromagnetic sensors (Flock of Birds Ascension Technologies Inc., Burlington, VT) attached at the following locations: (1) medial aspect of the torso at C7; (2) medial aspect of the pelvis at S1; (3) distal/posterior aspect of the throwing humerus; (4) distal/posterior aspect of the throwing forearm; (5) distal/posterior aspect of the non-throwing humerus; (6) distal/

posterior aspect of the non-throwing forearm; (7) distal/posterior aspect of the stride leg shank; (8) distal/posterior aspect of the stride leg femur; (9) distal/posterior aspect of the non-stride leg shank; and (10) distal/posterior aspect of the non-stride leg femur (Myers, Laudner, Pasquale, Bradley, & Lephart, 2005). Following the attachment of the electromagnetic sensors, an eleventh sensor was attached to a wooden stylus and used to digitize the palpated position of the bony landmarks (Myers et al., 2005; Wu et al., 2002, 2005). Participants were instructed to stand in the anatomical neutral position while selected body landmarks were accurately digitized. A link segment model was developed through digitization of joint centres for the ankle, knee, hip, shoulder, T12–L1, and C7–T1. The spinal column was defined as the digitized space between the associated spinous processes, whereas the ankle and knee were defined as the midpoints of the digitized medial and lateral malleoli, and medial and lateral femoral condyles, respectively. By virtue of the least-squares method (McGregor, Zeenat, & Bull, 2007), the hip and shoulder joint centres were defined.

Following all set-up and pre-test protocols, participants were allotted an unlimited time to perform their own specified pre-competition warm-up routine. During this time, participants were asked to spend at least 5 min of their warm-up throwing from the indoor pitching surface to be used during the test trials. After completing their warm-up and gaining familiarity with the pitching surface, each participant threw a series of maximal-effort fastballs for strikes towards a catcher located the regulation distance from the pitching mound (12.2 m). The pitching surface was positioned so that the participant's stride foot would land on top of a 40 × 60 cm Bertec force plate (Bertec Corp, Columbus, OH), which was anchored into the floor. For the current study, those data from the fastest pitch passing through the strike-zone were selected for detailed analysis (Guido et al., 2009; Oliver & Keeley, 2010a, 2010b; Rojas et al., 2009). Pitch velocity was determined by a JUGS radar gun (OpticsPlanet, Inc., Northbrook, IL) positioned at the base of the pitching surface and directed towards home plate.

Raw data regarding sensor orientation and position were transformed to locally based coordinate systems for each of the respective body segments. Euler angle decomposition sequences were used to describe both the position and orientation of the torso relative to the global coordinate system (Wu et al., 2002, 2005). The use of these rotational sequences allowed the data to be described in a manner that most closely represented the clinical definitions for the movements reported (Myers et al., 2005).

Data analysis

Data were analysed in the current study using the statistical analysis package SPSS v.15.0 for Windows. Data were collected and calculated for the fastest strike for all sEMG, kinematic, and kinetic parameters. Pearson product–moment correlation coefficients were calculated to examine the relationship between gluteal activity, hip and knee kinematics, and ground reaction forces during the delivery phase of the windmill softball pitch (Figure 1). Correlations were considered statically significant at $P < 0.05$. Werner et al. (2005) described the delivery phase as having two temporal events: from top of backswing to stride foot contact, and from stride foot contact to ball release. Stride foot contact was determined when the participant landed on the Bertec force plate (Bertec Corp, Columbus, OH) anchored into the floor of the pitching surface. These dependent variables were collected from stride foot contact to ball release.

Results

Average ball velocity was $24.1 \pm 1.4\ \mathrm{m \cdot s^{-1}}$ (54.1 ± 3.1 mph). Means and standard deviations

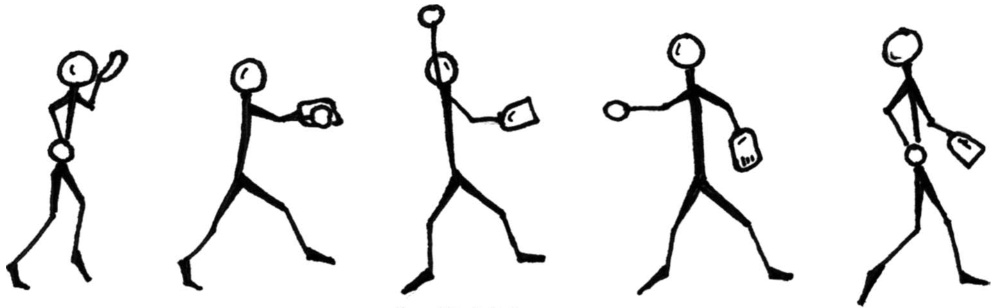

Figure 1. The delivery phase was described from top of backswing to stride foot contact and on to ball release.

of percent MVIC of the gluteal muscle group are presented in Figure 2. Kinetic (Table I) and kinematic variables (Table II) are presented below. There were positive relationships between ball velocity and ground reaction force ($r = 0.758$, $n = 10$, $P = 0.029$) as well as ball velocity and non-stride leg gluteus maximus ($r = 0.851$, $n = 10$, $P = 0.007$) and gluteus medius ($r = 0.760$, $n = 10$, $P = 0.029$) muscle activity, while there was no notable relationship between knee valgus and muscle activation (Table III). Other notable demographic findings were that those participants who exhibited greater stride length, as defined by top of backswing occurring before stride foot contact, demonstrated smaller breaking forces than participants with shorter stride lengths (32 ± 13% body weight vs. 41 ± 9% body weight). In addition, it should be noted that as the medial (Fz) forces increased, stride leg gluteus maximus experienced decreased muscle activation.

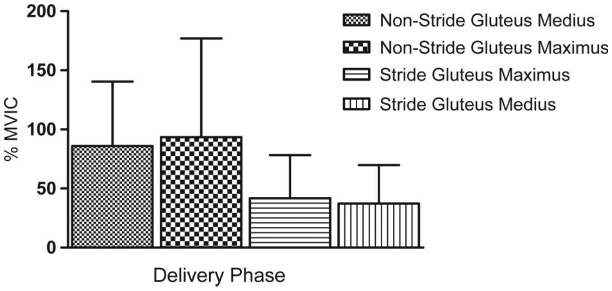

Figure 2. Means and standard deviations of the gluteal musculature, presented as a percentage of MVIC, during the delivery phase of the windmill pitching motion.

Table I. Means and standard deviations for ground reaction forces at stride foot contact as a percentage of the participant's body weight.

	Breaking force (Fx)			Vertical force (Fy)			Medial/lateral force (Fz)		
	mean	*s*	*n*	mean	*s*	*n*	mean	*s*	*n*
Phase 3	36	10	10	179	38	10	12	5	10

Table II. Means and standard deviations of degree of abduction angle for the hip and knee.

	Stride hip abduction			Stride knee abduction		
	mean	*s*	*n*	mean	*s*	*n*
Phase 3	−38.96	9.40	10	−3.91	7.10	10

Note: A negative value indicates adduction.

Discussion

This is the first study to investigate ground reaction forces, kinematics, and muscle activation during the windmill softball pitch. It is evident that the participants generated large breaking and vertical forces to drive towards the plate in order to produce the greatest ball velocity. Breaking forces as a percentage of body weight were 36 ± 10% body weight for all participants. When examining vertical forces, the average was 179 ± 38% body weight. However, those with longer stride lengths did exhibit greater vertical forces than those with shorter stride lengths. It has been reported that individuals with longer stride lengths have greater ball velocity (Guido et al., 2009). In the current study, participants who threw with higher ball velocities exhibited greater vertical ground reaction forces than those with lower ball velocities. In addition, it should be noted that the average ball velocity reported in this study is similar to those reported in previous studies (Guido et al., 2009; Werner et al., 2005).

Kinematics of the hip and the knee were reported as negative representing a medial direction or an adducted position. There were no significant relationships between hip or knee kinematics and stride length, muscle activations or ground reaction forces. Knee abduction angle was of interest because of its relevance to lower extremity injuries (Ford, Myer, & Hewett, 2003; Hewett et al., 2005; McLean, Huang, & van den Bogert, 2005). It is known that female athletes who participate in high-risk sports are at 4–6

Table III. Correlation matrix.

	Stride knee abduction	GRF	Velocity	Non-stride gluteus medius	Stride gluteus medius	Non-stride gluteus maximus	Stride gluteus maximus
SKA		−0.125	−0.113	−0.240	0.593	−0.300	0.625
GRF	−0.125		0.758*	0.508	0.192	0.610	0.245
Velocity	−0.113	0.758*		0.760	−0.203	0.851	0.158
NS GMed	−0.240	0.508	0.760*		−0.278	0.621	0.226
S Gmed	0.593	0.192	−0.203	−0.278		−0.230	0.708
NS Gmax	−0.300	0.610	0.851*	0.621*	−0.230		0.141
S Gmax	0.625	0.245	0.158	0.226	0.708	0.141	

*Significant at $p < 0.05$.

times greater risk of sustaining a knee injury than their male counterparts (Hewett et al., 2005). Thus with the increased ground reaction forces, it was of interest to examine the knee abduction angle of the stride leg at stride foot contact. Ligamentous injuries of the knee have not been prevalent in injury reporting for softball pitchers (Hill et al., 2004; Loosli et al., 1992), although the increased demands upon the knee due to the high ground reaction forces should be of concern.

The present study reported knee abduction angle during stride foot contact. However, the average angle is similar to that of other dynamic movements such as jumping (Ford, Shapiro, Myer, van den Bogert, & Hewett, 2010). With the low degree of knee abduction during stride foot contact of the windmill softball pitch, it is no surprise few ligamentous injuries to the knee in windmill softball pitchers have been reported. However, high numbers of low back, hip, and pelvis injuries have been documented (Loosli et al., 1992).The area of the low back, hip, and pelvis serve as the second most prevalent injury area in windmill softball pitchers to that of the shoulder (Hill et al., 2004).

If the majority of injuries are sustained to the low back, hip, and pelvis, the mechanics of the pelvis and torso that encompass the low back and hip should be addressed in an attempt to decrease the risk of lower extremity injuries in pitchers. The present study reported an average stride hip abduction angle of -38.96°, which indicates that at stride foot contact the hip/pelvis was tilted towards the non-stride leg. The tilting of the hip/pelvis is probably the cause of the decreased stride leg gluteal muscle activation as well as an increased stride leg knee abduction angle. In addition, the gluteal muscle activations of the stride leg during the delivery phase of the softball pitching motion demonstrated pelvic stabilization and torque generation in preparation for ball release. As the windmill softball pitcher is in her stride just prior to stride foot contact, the non-stride gluteus medius and maximus have to be activated in an attempt to stabilize the pelvis while on single leg support. It is the gluteus maximus that extends the hip while the gluteus medius acts to externally rotate the hip. The stride leg gluteus maximus and medius act to post the stride leg in preparation for ball release. Typically, the gluteal muscle group provides stabilization when on single leg support. Pelvic stabilization is important for efficient energy transfer up the kinetic chain from the hips to the pelvis and scapula on to the shoulder, elbow, hand, and wrist for ball release. This action is evident in that there was greater activation of the non-stride leg gluteus maximus in pitchers with greater ball velocities.

Regarding the observed decrease in gluteus maximus muscle activation and increase in medial (Fz) forces, the gluteus maximus originates at the external surface of the ilium and dorsum of the sacrum and attaches to the iliotibial track and greater trochanter. It functions to extend and assist in abduction of the thigh. It has been shown that when the lumbopelvic–hip complex is weak, structural abnormality will result in femoral internal rotation (Wilson, Dougherty, Ireland, & Davis, 2005).

The present results show greater activation of the non-stride leg gluteal muscle group compared with that of the stride leg. The upper extremity is dependent on lower extremity muscle activation, which may help to explain the muscle activation results of the non-stride leg. The function of the non-stride leg is to generate momentum to drive the pitcher towards home plate. During the stride phase, the only contact the pitcher has with the ground is with the non-stride leg. While on single leg support of the non-stride leg, the gluteal muscles of the non-stride leg have to counterbalance the loss of contralateral support and stabilize the pelvis. At the point of stride foot contact, momentum from the non-stride leg is transferred across the stabilized pelvis to the stride leg and the gluteal muscles act eccentrically to slow the transfer of momentum. The stride leg then acts as the breaking or decelerating force to slow the transfer of energy as the ball is released. The muscle activation of the non-stride leg gluteal muscle group as well as the decreased activation of the stride leg gluteal group could allow for increased hip abduction and external rotation, thus increasing compressive forces on the lumbar and lower thoracic vertebra. Since these data are only representative of a small group, further research is warranted in attempt to explain these activations and attempt to shed light on injury prevention.

It should be noted that it is the activation of the gluteal muscle group and its stability that allows for efficient energy transfer from the proximal core segments to the most distal segments of the upper extremity for ball release. It is the movements of the proximal lower extremity that dictate the movements of the upper extremity. Thus, from a rehabilitation and conditioning standpoint, awareness of body position and postural control is essential in dynamic sequential segmental motion. In an attempt to condition dynamic sequential muscle activation, the emphasis should be on postural awareness and neuromuscular control (Oliver, 2011).

A limitation of the present study is the low number of participants and the wide range of pitching abilities from age 15 to 20 years. With this wide maturation range, ball velocity varied from 51 to 57 mph. Although the number of participants was low, they did account for the majority of softball pitchers available within the area. Due to the limitation of low numbers, it is advised that further research be done on softball pitchers in an attempt to confirm the data presented in the current study.

Our results show that windmill softball pitchers with higher ball velocities also had higher vertical ground reaction forces. This ball velocity–vertical ground reaction force relationship is in agreement with Guido et al. (2009), where the greater vertical forces experienced by the stride leg allowed for a more forceful propulsion and greater ball velocity. In addition, as the medial (Fz) forces increased, stride leg gluteus maximus and medius had decreased activation. The gluteus maximus acts to extend the hip and then allows for external rotation of the hip. The decreased activation of the gluteus maximus of the stride leg indicates that it was not as active in externally rotating the stride hip, thus resulting in increased medial ground reaction forces. Understanding the magnitude and direction of ground reaction forces is essential for the rehabilitation and strength training of softball pitchers. From a kinematic chain standpoint, this decreased activation might result in a decreased rate of axial pelvis rotation throughout the delivery phase of the windmill softball pitch. In an attempt to increase gluteal muscle activation, the focus should be on hip extension and lumbopelvic–hip complex postural control (Oliver, 2011).

Previous research (Guido et al., 2009) has emphasized the importance of the core musculature in softball pitchers. However, the musculature most commonly mentioned has been the transverse abdominis and obliques. The core has been described as the lumbo-pelvic-hip complex that incorporates anterior, posterior, medial, and lateral musculature (Leetun, Ireland, Wilson, Ballantyne, & Davis, 2004). Trunk/torso/core stability describes the ability of the body to maintain or resume a position of the torso after both static and dynamic muscular contractions (Zazulak, Hewett, Reeves, Goldberg, & Cholewicki, 2007), or the product of motor control of the lumbo-pelvic-hip complex (Leetun et al., 2004) often referred to as ‘‘postural control’’. We also endorse the core musculature for adequate strength and conditioning of softball players. In addition to the anterior musculature of the core, we recommend that the entire lumbopelvic–hip complex be addressed in an attempt to activate the complete core. As the gluteal muscle groups are a major component of the lumbopelvic–hip complex, strength and conditioning should focus on their functionality (Oliver, 2011).

Our results should benefit rehabilitation and prevention programmes targeting windmill softball pitchers. With the quantification of the forces placed on the lower extremity, physical therapists and athletic trainers now have a foundation on which to base their lower extremity or more commonly their low back rehabilitations. Based on the disproportionate muscle activation of the stride and non-stride gluteal muscle groups, a few basic assumptions can be made. If the non-stride gluteal muscle group is highly active during ball release, accompanied with excessive vertical ground reaction forces on the stride leg, one may choose to address lengthening and strengthen the musculature of the stride side as well as strengthening the musculature of the non-stride side. However, a focus on bilateral dynamic movement is most warranted (Oliver, 2011).

From the current and previous studies (Guido et al., 2009; Werner et al., 2005) there is evidence of high ground reaction forces being experienced by the stride leg of windmill softball pitchers. Proper conditioning of the lumbopelvic–hip complex, including the gluteals, is essential. Although this study only examined ground reaction forces of the stride leg, the muscle activations were of both legs. With the non-stride leg generating the propulsive force for energy generation, it is further recommended that not only additional studies be conducted on the musculature of the lower extremity but also on the ground reaction forces experienced by the non-stride leg in windmill softball pitchers. However, from the data presented, it is evident that strength and conditioning of the gluteal muscle group bilaterally is salient in the windmill softball pitch.

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