Title: Mechanical work performed by distal foot-ankle and proximal knee-hip segments during anticipated and unanticipated cutting

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Bernard X.W. Liew, PhD [a]

Laura Sullivan BSc (Honours)[b]

Susan Morris, PhD [b]

Kevin Netto, PhD [b]

[a] School of Sport, Rehabilitation and Exercise Sciences, University of Essex, Colchester, Essex, CO4 3SQ, United Kingdom

[b] School of Physiotherapy and Exercise Sciences, Curtin University, GPO Box U1987, Perth, WA 6845, Australia.

Corresponding author: Dr Bernard Liew, S School of Sport, Rehabilitation and Exercise Sciences, University of Essex, Colchester, Essex, CO4 3SQ, United Kingdom; E-mail: bl19622@essex.ac.uk, liew_xwb@hotmail.com

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Abstract

Side-step cutting is a common evasive maneuver which is typically performed without prior anticipation. Studies quantifying joint work and its inter-joint proportions in cutting have not accounted for work done by the foot, even though this segment has been shown to be an important source of mechanical work in walking, running, and landing. The aims of this study were to: (1) quantify the magnitude of foot work performed and provide a more precise account of percentage joint work during cutting, and (2) examine the effect, a lack of anticipation had on these variables. Three-dimensional motion capture with forceplates were used to assess the cutting behaviour of 17 healthy participants. All participants performed a 45° cut with an approach speed of 4 m/s. Hip, knee, and ankle joint work were calculated using inverse dynamics; whilst foot work was quantified using the Unified-Deformable foot method. The foot contributed up to 12.45% and 3.09% of total limb negative and positive work, respectively. Unanticipated cutting significantly reduced ankle positive work (-0.09 J/kg [95% CI -0.13 to -0.06], $P < 0.001$) and significantly reduced percentage ankle positive work (-2.17% [95% CI -3.47 to -0.86], $P = 0.001$). The foot performs as much negative work as the hip but had only a minor contribution to positive work during cutting. Anticipation had a negligible influence on joint work and its inter-joint proportions. The foot should not be neglected in understanding whole-body dynamics during cutting, with greater understanding of its function potentially useful for informing athletic footwear design and cutting technique.

Key Words: Side-step cutting; Change of Direction; Joint work; Coordination.

1. Introduction

Side-step cutting is commonly employed in sport, and mechanical work must be performed to alter the direction of movement (Havens and Sigward, 2015). More than a third of the negative work performed during cutting happens at the knee and ankle joints while more than a third of the positive work is performed at the hip and ankle (David et al., 2018). Across walking, running and drop landing, the foot can contribute up to 22% of the total lower limb joint work (Arch and Fylstra, 2016; Olsen et al., 2019; Zelik et al., 2015). A previous study has reported that a reduction in distal ankle loading resulted in a compensatory increase in proximal knee loading during cutting (Wannop et al., 2014). Similar alterations in distal foot work may incur similar proximal compensatory mechanisms, although foot work during cutting has not been reported. Understanding the mechanical function of the foot in cutting is important as it may have implications for athletic footwear design as well as cutting technique modification (Worobets and Wannop, 2015).

When the direction of the cut is unanticipated, the roles of individual joints can change. When more time is allowed for cutting (i.e. anticipated), participants can pre-orientate their centre of mass (COM) prior to planting the cutting limb, requiring less turning and force to occur during the actual cut (Lee et al., 2017). In unanticipated cutting, the cutting foot is positioned further laterally from the COM, to generate more force in order to redirect the COM direction (Lee et al., 2017). Greater cutting width in unanticipated cutting would require greater hip mobility, and increase the external ground reaction force (GRF) lever arm to the hip joint centre, and contributing to greater hip kinetics compared to anticipated cutting (Meinerz et al., 2015; Whyte et al., 2018).

The primary purpose of this study was to quantify the magnitude of foot work during cutting and examine the effect, a lack of anticipation had on foot work. We hypothesized that like the ankle (Brown et al., 2014), anticipation would have no effect on foot work. The secondary purpose of this study was to provide a more precise account of the percentage joint work performed during cutting and examine the effect, a lack of anticipation had on changes to percentage joint work. We hypothesized that hip negative work and its percentage would increase with unanticipated compared to anticipated cutting.

2. Methods

2.1. Participants

Seventeen healthy participants were included for this study (10 M, 7 F, mean (standard deviation (SD)) age of 22.5 (3.1) years, height of 1.7 (0.1) m, body mass of 68.0 (12.0) kg). Participants were included if they were free from any lower limb injuries or pain in the past 3 months, or any previous knee ligamentous injuries, and females who were pregnant. All participants gave written consent and ethical approval was provided by Curtin University Human Research Ethics Committee (RD-41-14).

2.2. Side-step cutting

Participants performed cutting in their preferred running shoes, to facilitate a more natural cutting pattern, compared with cutting in a standardized footwear. For all trials, participants cut on the leg they would stand on when they kicked a ball (Rahnama et al., 2005), which was the left limb for all participants. Cutting was performed over two anticipatory conditions, the order of which was randomized.

For anticipated condition, participants were instructed to cut with their left foot on a force plate (AMTI, Watertown, MA), in the direction 45° towards the right (Figure 1). In the unanticipated condition, either speed gate four (G4) or G3 would be triggered when participants crossed G2. Participants would cut toward the right if G4 was triggered but continue running straight if G3 was triggered. The elapsed time from the trigger at G2, to the appearance of the triggered light in G3 or G4 was 600 ms (Brown et al., 2014).

A minimum of a 10 m run up distance was provided to participants to reach the desired speed of 4 m/s (+/- 10%). A successful trial was accepted if the participant performed the cutting manoeuvre within the velocity range and demarcated floor strip (Figure 1). A minimum of three successful trials for each condition was accepted, with an inter-trial rest duration of 60 s provided.

2.3. Data measurement and processing

Reflective markers were placed on the thorax, pelvis, bilateral thigh, shank and foot segments (supplementary material). Kinematics were captured using an 18-camera motion analysis system (VICON T-series, Oxford Metrics, UK) at 250 Hz with synchronised GRF at 1000 Hz. Both kinematic and force data were low-pass filtered (4^{th} Order, zero lag, at 18 Hz). Initial contact and toe-off events were determined using 20 N force plate threshold.

Foot power (P_{foot}) was calculated using the Unified-Deformable foot method (see supplementary for method) (Takahashi et al., 2012). The term "foot" presently reflects the foot-shoe complex, and foot work thus represents the work performed by both the foot and the shoe (Arch and Fylstra, 2016; Bruening et al., 2018). Inverse dynamics was used to derive joint power of the ankle, knee and hip (Liew et al., 2018). Total negative joint work was calculated by summation of the negative work performed by the foot, ankle, knee, and hip;

and similar calculations were performed to derive total positive joint work (Liew et al., 2016). Joint work was scaled to a percentage of a participant's body mass. Percentage negative and positive work was derived by taking each work value as a fraction of total negative and positive work.

2.4. Statistical analysis

Spatiotemporal characteristics of approach COM speed, cut angle, initial contact and toe-off COM speed, and stance duration are summarized in Table 1. COM speed was measured by the COM anterior-posterior direction speed after passing G1 (Figure 1). Differences between cue conditions in the six spatiotemporal variables were assessed using linear mixed models, as described below.

The response variables were the negative and positive work, as well as their corresponding percentage total negative and positive limb work, of the foot, ankle, knee, and hip joints. The effect of anticipation on the response variables was modelled using linear mixed models, and a subject-specific intercept was included in the models. Significance for each fixed effect predictor was determined using an alpha of 0.05. All statistical analyses were performed in R software.

3. Results

All spatiotemporal variables were significantly different between cue conditions (Table 1). The foot contributed between 0.36 to 0.37 J/kg and 0.06 to 0.07 J/kg of negative and positive work, respectively (Figure 3); which constituted between 12.42 to 12.45% and 2.62 to 3.09% of total limb negative and positive work, respectively (Figure 4). Compared to anticipated, unanticipated cutting significantly reduced ankle negative work (by a mean and 95% confidence interval [CI] of -0.07 J/kg [-0.11 to -0.03], P = 0.001), ankle positive work (by -0.09 J/kg [95% CI -0.13 to -0.06], P < 0.001), and percentage ankle positive work (by -2.17% [95% CI -3.47 to -0.86], P = 0.001). Unanticipated cutting significantly increased foot positive work (by 0.01 J/kg [95% CI 0.003 to 0.02], P = 0.003), percentage foot positive work (by 0.47% [95% CI 0.20 to 0.74]), and percentage hip negative work (by 1.34% [95% CI 0.22 to 2.47]).

Table 1. Spatiotemporal characteristics of cutting

	Anticipated	**Unanticipated**	**Statistical value**
Approach speed[m1]	4.217 (0.360)	3.908 (0.339)	P < 0.001
Initial contact speed (m/s)[m2]	3.539 (0.425)	3.393 (0.437)	P < 0.001
Toe-off speed (m/s)[m`3]	2.697 (0.306)	2.576 (0.310)	P < 0.001
Turn angle (°)[m4]	41.124 (5.558)	38.190 (5.956)	P < 0.001
Cut angle (°)[m5]	25.308 (7.476)	22.297 (9.074)	P = 0.007
Stance duration (s)	0.269 (0.039)	0.282 (0.052)	P < 0.001

m1 = 10-frame average of centre of mass (COM) of model velocity in LAB's Y-axis (direction of travel) when COM was visually inspected to be straight.
m2 = 10-frame average of the resultant scalar of the three-dimensional COM velocity vector before initial contact, inclusive.
m3 = 10-frame average of the resultant scalar of the three-dimensional COM velocity after toe-off, inclusive.
m4 = inner dot product of two COM velocity vectors: vector one (between 1st and 10th frame of m1) and vector two (between 1st and 10th frame of m3)
m5 = inner dot product of two COM velocity vectors: vector one (between 1st and 10th frame of m2) and vector two (between 1st and 10th frame of m3)

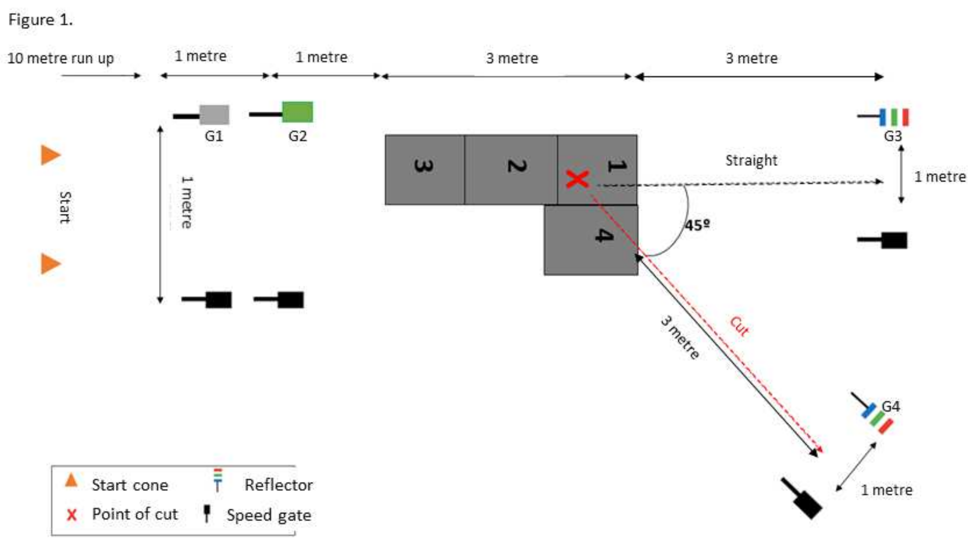

Figure 1

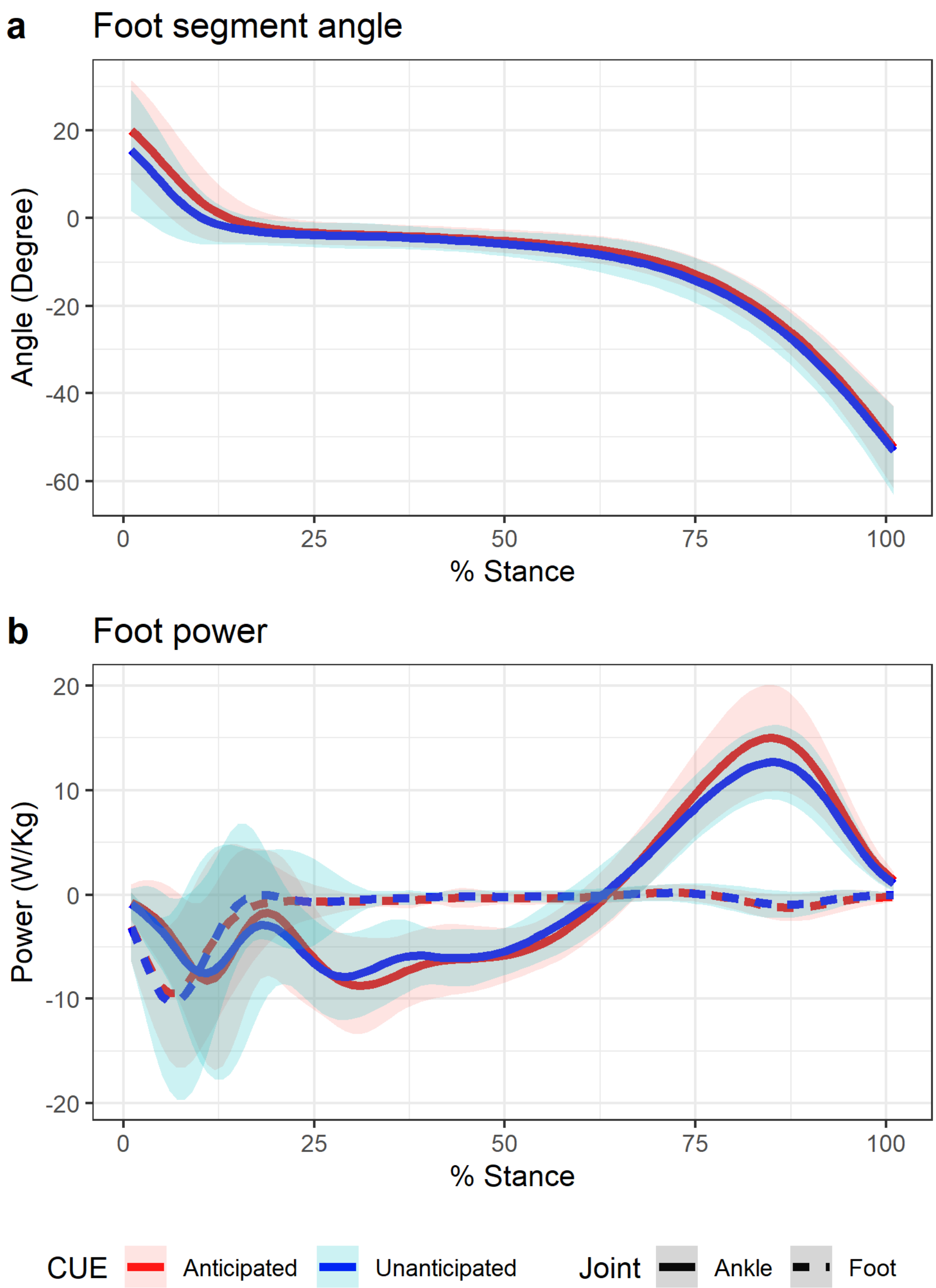
a
Foot segment angle
Angle (Degree)
20
0
-20
-40
-60
0
25
50
75
100
% Stance
b
Foot power
Power (W/Kg)
20
10
0
-10
-20
0
25
50
75
100
% Stance
CUE
Anticipated
Unanticipated
Joint
Ankle
Foot

Figure 2

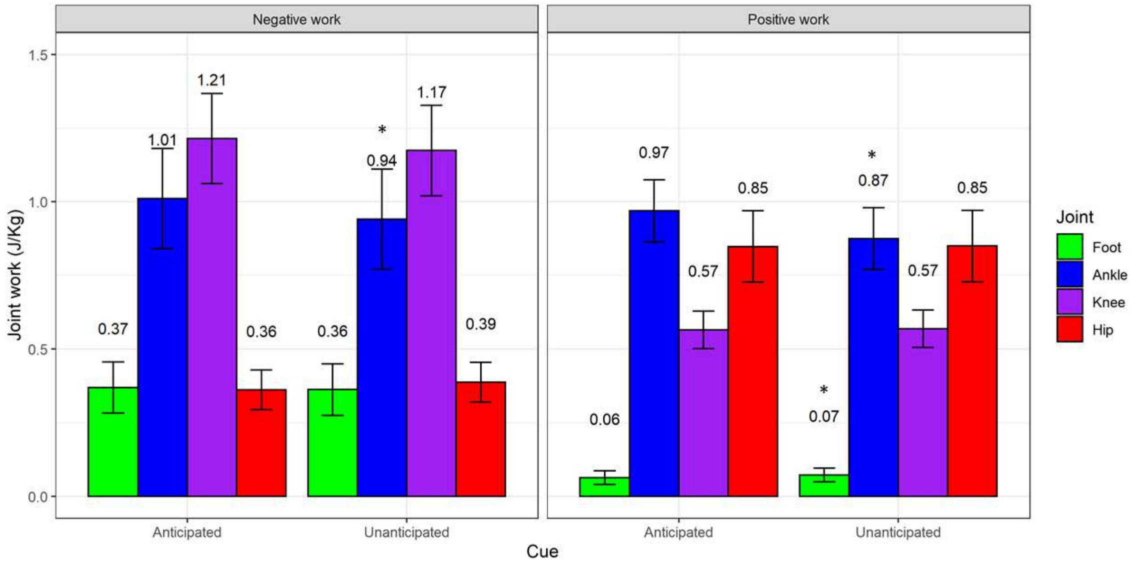

Figure 3

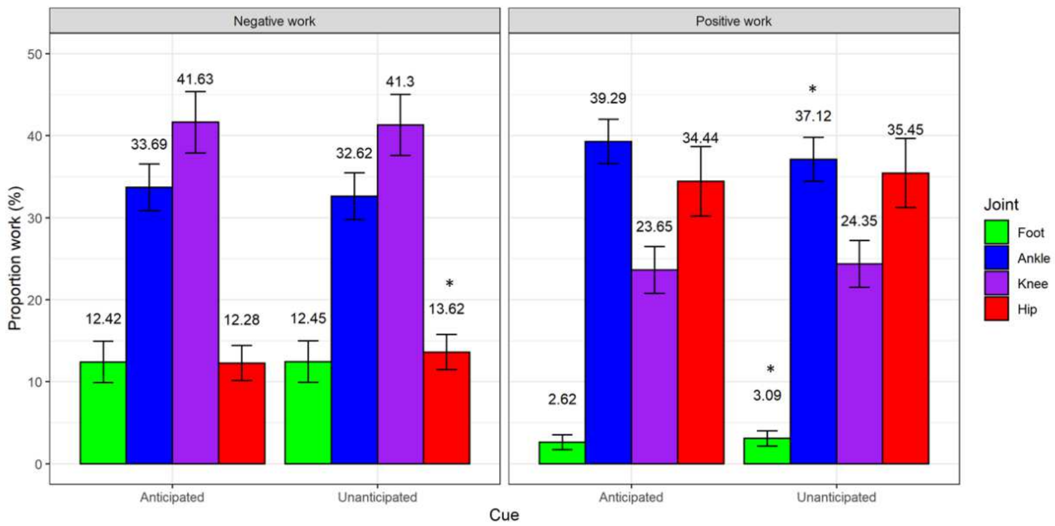

Figure 4

4. Discussion

This paper quantified the role of the foot during anticipated and unanticipated cutting. Against the first hypothesis, unanticipated cutting reduced ankle negative work and positive work, and significantly increased foot positive work. In partial agreement with our second hypothesis, unanticipated cutting only significantly increased percentage hip negative work compared to anticipated cutting.

A previous review reported that slower approach speeds are associated with reduced joint kinetics (Dos'Santos et al., 2018). It is unlikely that the alterations in mechanical work between anticipatory cues was driven solely by a reduction in approach speed, given that an increase in positive foot work with unanticipated cutting was observed compared to anticipated cutting. The magnitude of influence of anticipatory cues on joint work may be functionally meaningful. This is supported by previous work which found that a 0.01 J/kg increase in foot positive work, and a 0.06 J/kg increase in ankle positive work are associated with a 1 m/s increase in running speed (Jin and Hahn, 2018; Kelly et al., 2018a). However, it is unlikely that the influence of anticipatory cues on percentage joint work (< 2%) is meaningful, considering that changing the foot strike pattern altered percentage ankle negative work in running by 22% (Stearne et al., 2014). A more precise assessment of the contribution of anticipatory cues on cutting mechanics may require controlling the approach speed, which should be further investigated.

Negative work performed by lower limb muscles is used for braking, with greater braking GRF leading to sharper cutting angles (Dos'Santos et al., 2018). Given that the foot performs as much negative work as the hip, management of foot work may be as important as management of hip work in optimizing cutting performance, especially at sharper cutting angles. The functional importance of the foot may increase when cutting with a forefoot compared to a rearfoot landing strategy (Donnelly et al., 2017). Switching from a rearfoot to a forefoot strike pattern in running increased negative foot work (Kelly et al., 2018b), and we predict that a similar technique switch in cutting would similarly increase negative foot work. Given that an increase in negative ankle work has been linked to greater risk of posterior calf injuries in running (Rice and Patel, 2017), an increase in negative foot work when cutting with a forefoot strike technique may increase the risk of foot injuries.

The present study's finding of greater percentage hip negative work during unanticipated compared to anticipated cutting has indirect support from some studies (Meinerz et al., 2015; Whyte et al., 2018), but not in others (Brown et al., 2014). Whyte et al. (2018) reported greater hip negative work in the transverse plane, with no change in negative work by the knee and ankle reported during unanticipated compared to anticipated cutting. Meinerz et al. (2015) reported a shift in net work performed towards a more negative value at the hip, but a less negative value at the knee and ankle during unanticipated compared to anticipated cutting. The lack of effect anticipatory cues had on hip negative work in Brown et al. (2014) could be that the influence of anticipatory cues on cutting was investigated during load carriage (Brown et al., 2014). Load carriage has been shown to increase leg stiffness (Lobb et al., 2019), which may involve an increase in hip stiffness, a reduction in hip displacement and hence negative hip work remained invariant.

A limitation of the present study was that our methods cannot partition work performed by individual structures within the foot. Based on a previous study in walking, foot power in the first half of stance was attributed to structures proximal to the midfoot (Takahashi et al., 2017), which is supported by our foot power waveforms (Figure 2). Another limitation could be that standardized footwear was not prescribed, which could increase inter-participant variability in joint work estimates. When running with a prescribed footwear, a previous study reported a predicted 95% CI range in hip, knee, and ankle negative work of 0.15, 0.19, 0.15 J/kg, respectively (Hashizume et al., 2018). Our predicted 95% CI range of the same variables during anticipated cutting was 0.34, 0.30, 0.13 J/kg, respectively. However, a study in walking reported similar inter-participant standard deviations of ankle work when comparing walking barefooted versus in their preferred shoe (Farinelli et al., 2019). It may be argued that using a preferred shoe would produce more ecologically valid understandings of cutting mechanics, than cutting in a prescribed footwear. Regardless, differences in foot mechanical work between different footwear types should be explored in future studies.

5. Conclusion

The foot performed less than 14% of the negative work and less than 3% of positive work, with the former representing as much percentage negative work performed at the hip. The foot should not be neglected in understanding whole-body dynamics during cutting, with greater understanding of its function potentially useful for informing athletic footwear design.

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Figure captions

Figure 1. Schematic layout of the laboratory and equipment (light gates [G] and forceplates [greyed squares]) during experimental testing. Participants always approached the cut in the direction from forceplate 3 to 1.

Figure 2. Observed mean values with error bars as one standard deviation of (a) sagittal plane foot-ground angle (+ value = dorsiflexion), and (B) ankle and foot power during the stance phase of cutting.

Figure 3. Predicted mean values with error bars as 95% confidence interval of the negative and positive work performed by each joint during cutting. Values are predicted using the linear mixed models. Values above the barplot reflect the mean values. * Significant difference between anticipated an unanticipated cutting.

Figure 4. Predicted mean values with error bars as 95% confidence interval of the percentage negative and positive work performed by each joint during cutting. Values are predicted using the linear mixed models. Values above the barplot reflect the mean values. * Significant difference between anticipated an unanticipated cutting.

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