Short communication

Stepping threshold with platform-translation and shoulder-pull postural perturbation methods

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ABSTRACT

The type of balance recovery, feet-in-place or stepping, is predicated on the perturbation intensity, often defined by the combination of applied force and displacement. Few studies examined the relationship between characteristics required to produce a stepping response with one of the postural perturbation methods. The purpose of this study was to investigate the relationship between perturbation characteristics (applied force and displacement) required to elicit a forward stepping response with platform-translation and shoulder-pull methods, and to establish whether a common set of perturbation characteristics existed across both perturbation methods. Fourteen young healthy males participated. Temporally unexpected platform translations and shoulder pulls were induced by release of free weights, which fell a controlled height exerting a pull on the platform or on the participant via a shoulder harness. Participants responded with either feet-in-place or stepping responses. The force and displacement were varied to investigate the range of force-displacement combinations required to elicit stepping responses. Force-displacement combinations that elicited stepping responses were recorded and normalized to the participant's body weight (BW) and the base of support (BOS; participant's foot length). The lowest force and associated displacement that elicited stepping responses showed an inverse linear relationship during both platform-translation and shoulder-pull trials. The lowest force-displacement combination common to both perturbation methods was found to be 8.75%BW and 105%BOS, which, in the future work, could enable a direct comparison of the neuromuscular and biomechanical responses to different perturbation methods in a manner that attempts to equilibrate the perturbation stimulus across the methods.

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1. Introduction

Surface-translation and cable-pull perturbation paradigms are among the most commonly used methods to elicit balance-correcting responses in postural perturbation studies (Jensen et al., 2001; Maki et al., 1990; Mansfield and Maki, 2009; Mille et al., 2003). Balance-correcting responses elicited with those methods range from feet-in-place ankle responses to change-in-support responses, such as a stepping or upper limb reaching. Broadly speaking, the individual response is predicated on the intensity of perturbation. In previous research where the translating platform method was used, the nature of the response was determined by a combination of platform acceleration and the duration of acceleration, or displacement during platform translation (Jensen et al., 2001; Maki et al., 1996). When utilizing the

motor driven cable-pull method to perturb balance, the nature of the response was determined by a combination of acceleration with which the cable was pulled and the displacement resulting from the pull (Mille et al., 2003; Rogers et al., 2001). No studies to date have directly compared platform-translation and shoulder-pull perturbation stimuli in order to examine the relationship between perturbation characteristics and the implications for eliciting a stepping response. Furthermore, no studies have defined the perturbation characteristics (applied force and displacement) that would enable a direct comparison of the neuromuscular and biomechanical responses to different perturbation methods that provide objectively similar perturbation intensities.

The purpose of this exploratory technical study was to, first, investigate the relationship between perturbation characteristics (applied force and displacement) required to elicit a forward stepping response with platform-translation and shoulder-pull methods, and second, establish whether a common set of perturbation characteristics existed across both perturbation methods.

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2. Methods

2.1. Participants

Participants were excluded if they reported a history of neurological or musculoskeletal disorders; or an injury, pain or surgery on their lower body or back in the six months prior to participation. Fourteen healthy males (age 25.5 ± 2.9 years, height 1.82 ± 0.05 m, body weight (BW) 80.6 ± 10.0 kg, foot length 27.5 ± 1.0 cm; mean ± SD) participated and provided informed consent prior to participation. The local institutional research ethics board provided approval of the methods used in this study.

2.2. Set-up and protocol

A custom-built postural perturbation system was used (Fig. 1a). Postural perturbations were created by release of free weights which were suspended by an electromagnet. When the magnet was released, the free weights fell a predetermined height, which was limited by the addition or removal of chain links, exerting tensions within steel aircraft cable that was attached to either the platform on which participants stood (platform-translation trials; PLAT; Fig. 1b) or to the participants upper-body via a shoulder harness (shoulder-pull trials; PULL; Fig. 1c). Any slack in the cable was removed prior to the weight drop. To allow a comparison between perturbation methods and characteristics, friction within the PLAT was estimated for a range of participant body weights and used to adjust the actual force applied to elicit the perturbation. The amount of friction was determined by iteratively increasing the amount of weight atop the platform in steps of 10 kg and measuring the force required to move the platform. A regression function was constructed and used to determine the adjusted pull force for each participant.

The PLAT and PULL trials were conducted as blocks and performed on two separate days to reduce fatigue associated with performing lengthy data collection; participants visited the laboratory twice. The two data collection sessions were counterbalanced across participants. Participants were barefoot throughout testing in order to standardize the protocol across participants and remove shoes as a potential confounder. Base of support (BOS) length was defined as the length of participant's feet. All trials were initiated with participants standing on the platform. During the PULL trials, the platform wheels were locked, to create a stable surface. Participants wore a shoulder harness during the PULL trials. The cables were linked to the shoulder harness at the level of manubriosternal joint from the front and at the T3/T4 vertebrae from the back. The cable was connected to the participant (for PULL trials) and to the platform (for PLAT trials) from both front and back to negate force of tension in the cable intended to remove of the slack, such that the perturbation force could be isolated. Unexpected posterior platform translations and anterior shoulder pulls were used to induce postural instability. Though participants knew the direction of the postural perturbation, timing of the weight release was randomly varied between 3 and 8 s. Participants were instructed as follows: "Behave as naturally as possible. If you don't have to take a step, don't take a step. If you feel the need to take a step to avoid falling, do take a step. Do what is natural to avoid falling."

The perturbation stimulus intensity was defined as the combination of applied force (%BW) and displacement (%BOS). The applied force ranged between 2.0%BW and 12%BW (4.45 N increments); displacement ranged between 50%BOS and 155%BOS (2.2 cm increments). The range of the parameters was chosen such that the lowest set of parameters would not cause any of the participants to step, while the highest set of parameters would cause all participants to step. The trials were blocked by applied force. The entire range of displacement iterations was applied within each force block, i.e. the testing began with the lowest weight
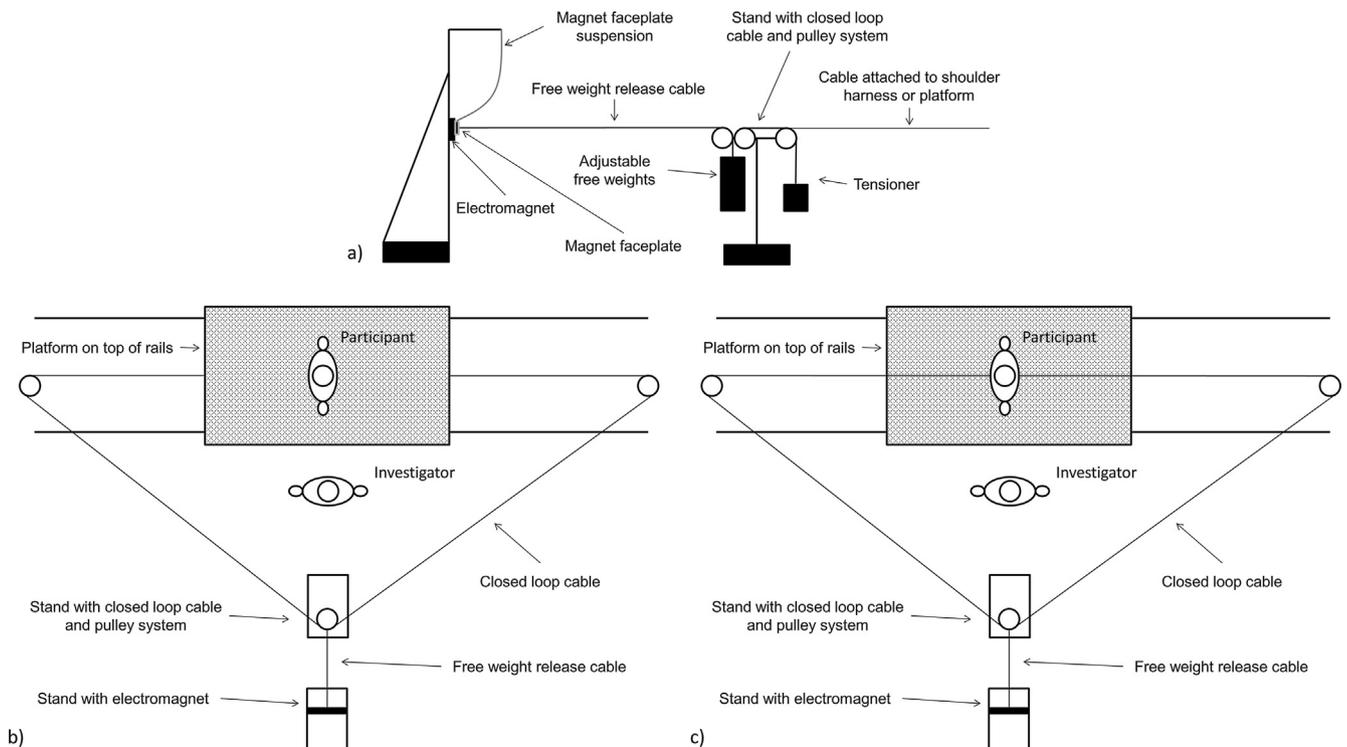

Fig. 1. A schematic diagram depicting the experimental setup. The figure (a) depicts the side view of electromagnet stand which was coupled with the closed loop cable and pulley system that allowed both anteriorly and posteriorly directed PLAT and PULL perturbations. The figures (b) and (c) depict the schematic top-down view of the experimental setup used in PLAT and PULL, respectively.

and the lowest displacement. The displacement was progressively increased from trial to trial until it reached the maximum value for each participant, while the force remained unchanged. The force was increased after the entire displacement range was tested; trials then resumed with the lowest displacement and the process was repeated until the entire range of displacement was applied. The process was repeated until the combination of the highest force and highest displacement was tested. This protocol was used with half of the participants ($n = 7$). For the remaining participants ($n = 7$), the protocol was conducted in reverse order to balance potential trial order effects, with testing starting with the largest force and the largest displacement. Participants completed one trial at each force-displacement combination. To offset the effects of fatigue, participants received rest breaks between the force trial blocks. On average, participants completed 2 to 3 trials per minute; while each session lasted approximately 1.5 to 2 h.

2.3. Measures of interest

To assess balance-correcting responses, an investigator (DV) stood next to the participant with the line of sight perpendicular to the line of step and in line with the adhesive tape placed in front of participant's toes. The tape was used to provide for consistent placement of feet and to identify two stepping threshold responses: (1) complete-step, anteriorly directed foot movement that was larger than 100%BOS (participant stepped over the tape), and (2) partial-step, defined as anteriorly directed foot movement that was smaller than 100%BOS (participant did not step over the tape), which were manually recorded by the investigator. The feet-in-place balance-correcting response was coded as 0, partial-step as 0.5, and complete-step as 1. The response codes were recorded in a blank version of the 16×14 cell force-displacement matrix (Fig. 2). The average value for each cell was calculated across all participants for the PLAT and PULL trials separately. The combination of lowest force and associated displacement, which produced the result of "1" across all matrices for PLAT and PULL trials, were mapped on a scatter plot.

2.4. Statistical analysis

All statistical analyses were conducted using JMP (v8.0, SAS Institute, North Carolina). A linear regression function was fitted to the complete-step threshold scatter plot data. The linear function fit was considered significant at $p < 0.05$. The pull weight and the pull displacement values were expressed as mean ± SE.

3. Results

The aggregate matrix of all individual force-displacement matrices was created for the PLAT (Fig. 3) and PULL (Fig. 4) trials, separately. For the PLAT trials, the combination of the lowest force and associated displacement that resulted in a complete-step response for all participants showed a significant ($r = -0.967$; $R^2 = 0.935$, df = 11, $p < 0.001$) linear inverse relationship between force and displacement. Likewise, for the PULL trials, complete-step data showed a significant ($r = -0.972$; $R^2 = 0.945$, df = 6, $p < 0.001$) linear inverse relationship between required force and displacement below 123%BOS. Above 123%BOS, a force of approximately 7%BW was required to elicit a complete-step balance-correcting response. The relationships between force and displacement required to elicit a stepping response for both perturbation methods are described in Fig. 5.

Force

Displacement (cm)	BOS %	13.4 / 2.0	17.8 / 2.7	22.3 / 3.3	26.8 / 4.0	31.2 / 4.7	35.7 / 5.3	40.1 / 6.0	44.6 / 6.7	49.1 / 7.3	53.5 / 8.0	58.0 / 8.7	62.4 / 9.3	66.9 / 10.0	71.3 / 10.7	75.8 / 11.3	80.3 / 12.0 (N / BW %)
13.2	49	0	0	0	0	0	0	0	0.5	0.5	0.5	1	1	1	1	1	1
15.4	57	0	0	0	0	0.5	0.5	0.5	0.5	0.5	1	1	1	1	1	1	1
17.6	65	0	0	0	0	0.5	0.5	0.5	0.5	0.5	1	1	1	1	1	1	1
19.8	73	0	0	0	0	0.5	0.5	0.5	0.5	0.5	1	1	1	1	1	1	1
22.0	81	0	0	0	0	0.5	0.5	0.5	0.5	1	1	1	1	1	1	1	1
24.2	90	0	0	0	0	0.5	0.5	0.5	0.5	1	1	1	1	1	1	1	1
26.4	98	0	0	0	0	0.5	0.5	1	1	1	1	1	1	1	1	1	1
28.6	106	0	0	0	0	0.5	0.5	1	1	1	1	1	1	1	1	1	1
30.8	114	0	0	0	0.5	0.5	1	1	1	1	1	1	1	1	1	1	1
33.0	122	0	0	0	0.5	0.5	1	1	1	1	1	1	1	1	1	1	1
35.2	130	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
37.4	139	0.5	0.5	0.5	1	1	1	1	1	1	1	1	1	1	1	1	1
39.6	147	0.5	0.5	0.5	1	1	1	1	1	1	1	1	1	1	1	1	1
41.8	155	0.5	0.5	0.5	1	1	1	1	1	1	1	1	1	1	1	1	1

Fig. 2. A sample map representation of force-displacement matrix for the range from feet-in-place (coded as 0) to partial step (coded as 0.5) to complete-step (coded as 1) for an exemplar participant with the weight of 68 kg and BOS length of 27 cm during PULL responses.

		Force															**BW % SE %**
		2.8	3.4	4.0	4.5	5.1	5.6	6.2	6.8	7.3	7.9	8.4	9.0	9.6	10.1	10.7	11.2	
		0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	
50.3	0.7	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.2	0.5	0.5	0.5	0.8	0.8	0.9	0.9	0.9	
58.3	0.6	0.0	0.0	0.0	0.1	0.2	0.1	0.1	0.3	0.5	0.6	0.5	0.7	0.9	0.9	0.9	0.9	
66.3	0.6	0.1	0.0	0.0	0.1	0.2	0.1	0.2	0.4	0.4	0.6	0.7	0.7	0.9	1	1	1	
74.2	0.6	0.0	0.0	0.0	0.0	0.2	0.1	0.1	0.5	0.6	0.7	0.8	0.8	0.9	1	1	1	
82.2	0.6	0.0	0.0	0.0	0.2	0.1	0.1	0.2	0.3	0.6	0.7	0.8	0.8	1	1	1	1	
90.2	0.6	0.0	0.0	0.1	0.0	0.2	0.1	0.3	0.3	0.7	0.8	0.8	1	1	1	1	1	
98.2	0.6	0.0	0.0	0.0	0.2	0.2	0.1	0.4	0.6	0.8	0.8	0.8	1	1	1	1	1	
106.2	0.7	0.0	0.0	0.0	0.2	0.2	0.1	0.5	0.5	0.8	0.9	0.9	1	1	1	1	1	
114.2	0.7	0.0	0.0	0.0	0.2	0.2	0.1	0.5	0.7	0.8	1	1	1	1	1	1	1	
122.2	0.7	0.0	0.0	0.0	0.2	0.2	0.1	0.6	0.7	0.8	1	1	1	1	1	1	1	
130.2	0.8	0.0	0.0	0.2	0.2	0.2	0.1	0.5	0.7	0.9	1	1	1	1	1	1	1	
138.1	0.8	0.0	0.0	0.1	0.2	0.2	0.2	0.6	0.7	1	1	1	1	1	1	1	1	
146.1	0.9	0.0	0.0	0.1	0.2	0.1	0.3	0.7	0.7	1	1	1	1	1	1	1	1	
154.1	1.0	0.0	0.1	0.1	0.2	0.3	0.2	0.7	0.8	1	1	1	1	1	1	1	1	
BOS %	**SE %**																	

(Left axis label: **Displacement**)

Fig. 3. A map representation of the force-displacement matrix for the range from feet-in-place to complete-step averages (*n* = 14) for each force-displacement combination for PLAT perturbations. The complete-step responses for all participants are coded as 1 and are coloured in light grey. The combination of lowest force and associated displacement, which produced the result of 1, is coloured in dark grey and represents complete-step threshold. The force and displacement values for each dark grey cell within the matrix were used to establish a complete-step threshold relationship.

The intersection between PLAT and PULL functions represents the smallest common force-displacement perturbation characteristics (8.75%BW and 105%BOS; Fig. 5) required to elicit a stepping response using both PLAT and PULL methods.

4. Discussion

The purpose of this exploratory technical study was to investigate the relationship between perturbation characteristics (applied force and displacement) required to elicit a forward stepping response with platform-translation and shoulder-pull methods, and to establish whether a common set of perturbation characteristics existed across both perturbation methods. An inverse linear force-displacement relationship was established for both platform-translation and shoulder-pull methods (Fig. 5); the results of the shoulder-pull method in the current study are in agreement with previously reported findings (Mille et al., 2003). The interpretation of the regression lines is such that any combination of force and displacement on, or above the regression lines would produce a complete-step response with the associated perturbation method. Interestingly, it appeared that with the shoulder-pull method, there was a minimum force threshold of approximately 7%BW required to elicit a complete-step response; since beyond approximately 123%BOS, participants did not show complete-step responses with any combination of force lower than 7%BW. With the platform-translation method, however, it appeared that there was no clear minimum force required to elicit a complete-step response in the range examined as the force-displacement relationship appeared to be linear throughout the data set. The differences between these patterns speak to fundamental differences in the nature of the perturbations; the interactions between perturbation and response being akin to those of a slip for the platform translation, and perhaps being bumped by a passerby for the pull perturbation. Common perturbation characteristics were observed to be 8.75%BW of force and 105%BOS of displacement, at the intersection between the PLAT and PULL regression lines. These characteristics represent the lowest force-displacement combination required to elicit a complete-step response with either perturbation method.

The current study differs from previous research (Jensen et al., 2001; Mille et al., 2003) in that both lower and upper body perturbations were investigated using common equipment, procedure, and participants. Further, unlike previous research (Mansfield and Maki, 2009) the current study investigated the stepping thresholds for both platform-translation and shoulder-pull perturbation methods over a range of perturbation intensities; perturbation characteristics common to both platform-translation and shoulder-pull perturbation methods were established, which will enable a direct comparison of the neuromuscular and biomechanical responses to different perturbation methods in a manner that attempts to equilibrate the perturbation stimulus across the methods.

This study is limited by the recruitment of male participants. Since the purpose of this study was to develop a method that would attempt to equate perturbation intensity across different perturbation types and to investigate the relationship between perturbation characteristics across perturbation methods, we opted to recruit a homogenous sample of participants. Future research should investigate the repeatability of stepping boundary profile measures across both platform-translation and shoulder-

<div align="center">Force</div>

Displacement		2.7 (0.2)	3.3 (0.1)	3.9 (0.1)	4.4 (0.1)	5.0 (0.1)	5.6 (0.1)	6.2 (0.1)	6.7 (0.1)	7.3 (0.1)	7.9 (0.1)	8.5 (0.1)	9.0 (0.1)	9.6 (0.1)	10.2 (0.2)	10.7 (0.2)	11.3 (0.2)	BW % SE %
50.7	0.7	0.0	0.0	0.0	0.1	0.2	0.2	0.5	0.4	0.3	0.4	0.5	0.5	0.5	0.5	0.5	0.6	
58.7	0.7	0.0	0.0	0.0	0.1	0.3	0.4	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.8	0.8	0.7	
66.7	0.6	0.0	0.0	0.0	0.3	0.4	0.4	0.5	0.5	0.6	0.6	0.7	0.8	0.9	0.9	0.9	0.9	
74.7	0.6	0.1	0.1	0.1	0.4	0.5	0.5	0.5	0.6	0.7	0.8	0.8	0.9	0.9	0.9	0.9	1	
82.7	0.6	0.0	0.1	0.1	0.4	0.5	0.6	0.6	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1	
90.7	0.6	0.1	0.2	0.2	0.5	0.5	0.6	0.6	0.8	0.9	0.9	0.9	0.9	1	1	1	1	
98.7	0.6	0.1	0.1	0.4	0.4	0.5	0.6	0.6	0.9	0.9	0.9	0.9	1	1	1	1	1	
106.7	0.6	0.1	0.3	0.4	0.5	0.5	0.7	0.8	0.9	0.9	0.9	0.9	1	1	1	1	1	
114.7	0.6	0.1	0.2	0.5	0.6	0.6	0.8	0.8	0.9	0.9	1	1	1	1	1	1	1	
122.7	0.7	0.1	0.3	0.5	0.6	0.7	0.8	0.9	1	1	1	1	1	1	1	1	1	
130.7	0.7	0.1	0.3	0.5	0.7	0.8	0.8	0.9	1	1	1	1	1	1	1	1	1	
138.7	0.8	0.2	0.3	0.5	0.7	0.8	0.8	0.9	1	1	1	1	1	1	1	1	1	
146.7	0.8	0.2	0.3	0.5	0.7	0.8	0.8	0.9	1	1	1	1	1	1	1	1	1	
154.7	0.9	0.2	0.4	0.5	0.7	0.8	0.8	0.9	1	1	1	1	1	1	1	1	1	
BOS %	SE %																	

Fig. 4. A map representation of the force-displacement matrix for the range from feet-in-place to complete-step averages (*n* = 14) for each force-displacement combination for PULL perturbations. The complete-step responses for all participants are coded as 1 and coloured in light grey. The combination of lowest force and associated displacement, which produced the result of 1, is coloured in dark grey and represents complete-step threshold. The associated force and displacement values for each dark grey cell within the matrix were used to establish a complete-step threshold relationship.
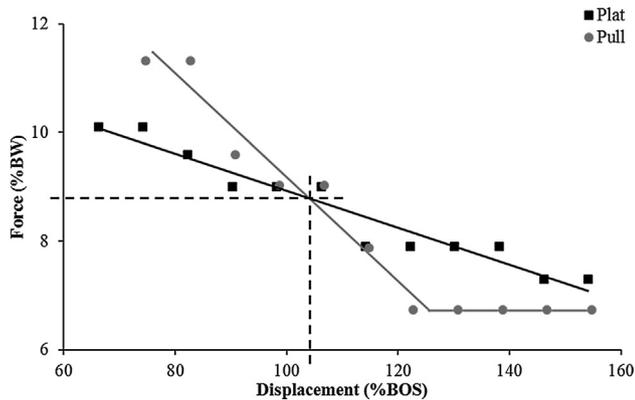

Fig. 5. The complete-step threshold force-displacement relationship for the PLAT and PULL perturbations depicted in the same figure. The approximate intersection between PLAT and PULL functions (intersecting black dash lines) represents common force-displacement perturbation characteristics (8.75%BW and 105%BOS) required to elicit a stepping response using both perturbation methods.

5. Conclusion

An inverse linear force-displacement relationship defining the stepping threshold for platform perturbations and upper-body pull perturbations has been identified. The intersection of these relationships will now be used to define specific perturbation characteristics to explore differences between platform translation and upper-body perturbations. The next steps may also include examination of special populations (e.g. older adults) to explore factors that may alter the parameters of these relationships.

Declaration of Competing Interest

The authors have no conflicts of interest to disclose.

pull methods and develop a robust statistical model that would allow for comparison across the stepping boundary profiles to be made. Further, in this study the threshold has been defined by the force-displacement characteristic at which all participants would take a step and, therefore, calculated as such; another way to determine the threshold would be to construct a probability distribution of stepping at a given range of forces and displacements.

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