Can Increased Locomotor Task Difficulty Differentiate Knee Muscle Forces After Anterior Cruciate Ligament Reconstruction?

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Changes in knee mechanics following anterior cruciate ligament (ACL) reconstruction are known to be magnified during more difficult locomotor tasks, such as when descending stairs. However, it is unclear if increased task difficulty could distinguish differences in forces generated by the muscles surrounding the knee. This study examined how knee muscle forces differ between individuals with ACL reconstruction with different graft types (hamstring tendon and patellar tendon autograft) and “healthy” controls when performing tasks with increasing difficulty. Dynamic simulations were used to identify knee muscle forces in 15 participants when walking overground and descending stairs. The analysis was restricted to the stance phase (foot contact through toe-off), yielding 162 separate simulations of locomotion in increasing difficulty: overground walking, step-to-floor stair descent, and step-to-step stair descent. Results indicated that knee muscle forces were significantly reduced after ACL reconstruction, and stair descent tasks better discriminated changes in the quadriceps and gastrocnemius muscle forces in the reconstructed knees. Changes in quadriceps forces after a patellar tendon graft and changes in gastrocnemius forces after a hamstring tendon graft were only revealed during stair descent. These results emphasize the importance of incorporating sufficiently difficult tasks to detect residual deficits in muscle forces after ACL reconstruction.

Keywords: knee injury, gait, OpenSim, musculoskeletal modeling

Physical rehabilitation after an anterior cruciate ligament (ACL) reconstruction seeks to restore stability, range of motion, muscle strength, and neuromuscular control of the knee joint.1 Prior research shows that ACL reconstructed (ACLR) knees often exhibit altered knee joint kinematics and kinetics across a variety of dynamic tasks.2–8 For example, individuals with ACL reconstruction may exhibit reduced knee joint excursions and moments when walking or jumping.9–11 These alterations in knee mechanics are thought to negatively affect the loading of the articular cartilage and increase the risk for degenerative changes such as osteoarthritis.12–16 Contributing to the alterations in knee joint loading are the forces generated by muscles acting directly on the knee joint. Postsurgical rehabilitation strategies, which employ a variety of dynamic tasks aimed at restoring the knee joint dynamic stability,17 would benefit from insight into how knee muscle forces during locomotor tasks might change after an ACL reconstruction.

Locomotor tasks can vary in difficulty depending on task demands.18,19 For example, descending stairs is inherently more difficult than overground level walking, as it requires controlled lowering of the center of mass and includes an increased risk of falling. Similarly, stair descent to another step is inherently more difficult than descending the final step to the floor, which is a more stable environment with a decreased risk of falling. It is important to note that a task’s difficulty also includes a person’s subjective perception of the task,20 which is independent of the task’s complexity.21,22 Task difficulty is also an important factor to consider when designing studies, as important between-group differences may only appear when a locomotor task is sufficiently difficult.23–25

Increasing the difficulty of locomotor tasks can magnify kinematic and kinetic differences between ACLR and healthy knees,2,5,26–27 likely due to the deficits in the ability to increase muscle forces and activation levels to meet the increase in mechanical loading of the knee during biomechanically challenging tasks.28,29 For example, we previously found that individuals with an ACL reconstruction exhibited significantly lower peak knee flexion moments than controls when descending stairs, a difference we did not detect during overground level walking.27 Furthermore, we observed that these differences were more pronounced when descending to another step as opposed to descending to the floor, suggesting that increased locomotor task difficulty was the primary driver of differences in joint mechanics between ACLR participants and controls. However, it is not known if this increased locomotor task difficulty could further detect differences in the generated knee muscle forces between ACLR participants and controls.

Potential alterations to knee muscle forces might also depend on which tendon is excised for the reconstruction procedure, as the intrinsic mechanics of the supporting musculature will be affected in unique ways.3,30 In the case of a patellar tendon (PT) graft excision, the quadriceps muscles are substantially weakened,31 whereas a hamstring tendon (HT) graft harvest can lead to weakness in knee flexion strength.1 Both types of grafts may also result in anterior knee pain,32 which may cause further adaptations to neuromuscular control during locomotion. We previously found that deficits in frontal plane adduction torque when descending...
suspect that knee muscle forces will also express graft-dependent differences with increased locomotor task difficulty.

The purpose of this study was to examine how the estimates of knee muscle forces differ between individuals with ACL reconstruction with different graft types (HT and PT autograft) and “healthy” controls when performing tasks with increasing locomotor task difficulty. We used an established musculoskeletal modeling and simulation approach to identify individual knee muscle forces in participants with a HT graft (ACLR HT), participants with a PT graft (ACLR PT), and control participants when walking overground and descending stairs. We hypothesized that knee muscle forces would significantly differ based on graft types and more difficult locomotor tasks would exacerbate these differences and better discriminate differences between ACLR HT, ACLR PT, and control participants.

Methods

Participants

Fifteen young adults (5 ACLR HT, 4 ACLR PT, and 6 uninjured controls) volunteered to participate in this study (Table 1). The participants with an ACL reconstruction had previously experienced an isolated ACL rupture and received surgical reconstruction using either a HT (ACLR HT) or a PT (ACLR PT) autograft at least 6 months and up to 15 months prior to the study sessions. We excluded ACLR HT and ACLR PT participants if they were obese (body mass index $\geq 30$), were unable to perform daily functional activities without using a knee brace, had a history of knee pain prior to their ACL injury and/or at the time of testing, had experienced a prior injury/surgery to the reconstructed knee or the contralateral knee, had received a revision ACL reconstruction, or had experienced severe damage to the meniscus or other knee ligaments at the time of the ACL injury, diagnosed by the operating orthopedic surgeon. We recruited healthy control participants to match the approximate age, height, weight, and activity level of the ACLR HT and ACLR PT participants. All experimental procedures were approved by the institutional review board of Northwestern University, and all participants provided written informed consent before participating in the study.

Experimental Data

Participants performed overground walking and stair descent in the laboratory as part of a separate study of knee joint kinetics, reported previously. Participants walked overground and downstairs at a comfortable, self-selected pace while wearing their own shoes. Stair descent was conducted on a portable set of stairs with 4 steps (step height = 7.5 in). Each task was performed at least 5 times with the leading limb as both the leg with the ACL reconstruction and the contralateral leg.

An 8-camera passive motion capture system (Motion Analysis Corp, Santa Rosa, CA) recorded the 3-dimensional trajectories of 32 markers placed on the participant’s torso, pelvis, and lower extremities at 120 Hz while force plates collected ground reaction data at 2400 Hz. We used 3 force plates mounted within the walkway (AMTI, Watertown, MA), and 2 force plates mounted within the bottom steps of the stairs (Kistler, Winterthur, Switzerland). We filtered marker trajectories (6 Hz) and ground reaction forces (15 Hz) using a fourth-order low-pass Butterworth filter.

We also recorded surface electromyographic (EMG) signals bilaterally at 2400 Hz using a multichannel EMG system (model MA-311; Motion Lab Systems, Inc, Baton Rouge, LA) from 7 lower limb muscles—vastus medialis, vastus lateralis, rectus femoris, semitendinosus, biceps femoris, medial gastrocnemius, and lateral gastrocnemius. After preparing the skin over the electrode site, surface EMG electrodes were placed over the target muscle bellies according to SENIAM guidelines (www.seniam.org). EMG signal quality was assessed during preliminary functional tasks, and electrode placements were adjusted as necessary. Raw EMG data were high-pass filtered at 30 Hz using a fourth-order Butterworth filter, full wave rectified, and then low-pass filtered at 6 Hz using a custom MATLAB script.

Musculoskeletal Modeling and Simulation

We used the processed marker trajectories and ground reaction forces and moments to generate participant-specific simulations of every trial (Figure 1). We restricted our analysis to the stance phase (foot contact through toe-off, as identified from ground reaction force data), yielding separate simulations for overground walking, step-to-floor stair descent, and step-to-step stair descent. In OpenSim, a lower-extremity model with 44 musculotendon actuators was first scaled to the anthropometrics of each participant during a static trial. We used a global optimization inverse kinematic routine to compute the pelvis, hip, knee, and ankle kinematics that minimized the error between the measured and simulated marker positions using a weighted least-squares approach. We then calculated joint moments using a residual reduction algorithm, which slightly alters model mass properties and joint kinematics to achieve more dynamic consistency between the joint kinematics and the ground reaction forces during inverse dynamics. The computed muscle control algorithm then determined the set of

<table>
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<th>Table 1 Group Summary Demographics</th>
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<tr>
<td>BMI</td>
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<td>Months postsurgery</td>
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Abbreviations: ACLR, anterior cruciate ligament reconstruction; BMI, body mass index; HT, hamstring tendon graft; PT, patellar tendon graft. Note: Data are reported as mean (SD). There were no significant differences between groups in the demographic variables.

Figure 1 — Snapshots from a simulation of the stance phase during (A) walking and (B) stair descent. Simulations begin with foot contact and end with toe-off. Muscle color indicates the simulated activation level, from fully activated (red) to fully deactivated (blue).
muscle excitations required to drive the model toward the experimentally measured kinematics. The computed muscle control muscle activations were constrained during stance using normalized EMG data. To assess the accuracy of the simulations, we compared our experimental data with simulated quantities. We compared the joint angles found using inverse kinematics to the muscle-actuated simulations and found that the average root mean square error was <2°. We also visually compared the simulated muscle activations to the normalized EMG activity (see Supplementary Material 1 [available online]).

We extracted the simulated muscle forces for the major muscles crossing the knee joint—vastus medialis, vastus lateralis, vastus intermedius, rectus femoris, semimembranosus, semitendinosus, biceps femoris, medial gastrocnemius, and lateral gastrocnemius. Muscle forces were time normalized to 101 points as a percentage (0%–100%) of the stance phase. Muscle forces were also amplitude normalized to the maximum isometric force of the generic model scaled by each participant’s mass.

Statistical Analysis

We evaluated between-group differences in muscle force using statistical parametric mapping (SPM), which compared the continuous muscle force at each percentage of stance phase. We chose to use SPM analysis so that we could examine each instance of the stance phase without specifying an area of interest, and thus, minimize any researcher bias toward a specific instance of stance (eg, peak angle or force). In other words, we used SPM to determine the regions of stance where statistical significance was observed (Figure 2). Using SPM, A 1-way analysis of variance was used to test for a main effect (α = 0.05) of subject groups (controls, ACLR HT, and ACLR PT) on muscle force during 3 separate tasks of increasing difficulty: level walking, stair descent to floor, and stair descent to step. SPM analyses were performed in MATLAB (SPM1D version M.0.4.6 in MATLAB; MathWorks, Inc, Natick, MA) using open-source codes (SPM1D, version M0.1; www.spm1d.org) that are described in detail elsewhere.

Briefly, SPM1D analysis first calculates a vector field of test statistics (F) at each instantaneous point across the stance phase gait cycle. To evaluate the significance of the vector field (F), SPM computes a critical F threshold (F*) that corresponds to α = 0.05 using random field theory wherein portions of the computed vector field (F) that exceeded the computed critical F threshold (F*) were considered significant. We tested the null hypothesis that knee joint forces did not differ between groups. When a significant main effect over a region of stance was identified by SPM, SPM post hoc analysis was performed using 2-sample t tests with a Bonferroni correction (adjusted alpha = 0.017). The 2-sample t tests tested 2 primary planned comparisons (ACLR HT vs controls and ACLR PT vs controls) and one secondary exploratory analysis (ACLR HT vs ACLR PT) (Figure 2). The comparison between ACLR HT versus ACLR PT was only performed as an exploratory analysis (1) because our primary interest was to identify how ACL reconstruction affects knee muscle forces during increasingly difficult tasks when compared with uninjured controls and (2) due to the sample size of the ACLR HT and ACLR PT groups. Similar to procedures described above, SPM(t) analysis computes a scalar field (t), which corresponds to α = 0.05 at each instantaneous point across the stance phase gait cycle. If any portions of the knee muscle forces exceeded this critical threshold (t*), then a significant difference between groups was considered present. We tested the null hypothesis that the knee muscle forces are similar across tasks in both ACLR HT participants, ACLR PT participants, and uninjured controls.

Results

We evaluated the stance phase for 162 separate simulations. The 1-way analysis of variances revealed a significant main effect of group for regions of stance phase during all 3 locomotor tasks (Table 2).

The quadriceps had long regions of significant differences during loading and midstance where both ACLR HT participants and ACLR PT participants exhibited significantly reduced muscle forces than control participants, primarily in the vasti muscles (Figure 3 and Supplementary Material 2 [available online]). These regions of significant differences within the vasti appeared consistently across all tasks, and the length of these regions increased when the task difficulty increased. ACLR HT participants...
demonstrated significantly reduced muscle forces than control participants during all tasks. In contrast, ACLR PT participants demonstrated significantly reduced muscle forces than the control participants only during the more difficult stair descent tasks. During the stair descent to step task, significant differences in vasti muscle force did not reappear in the latter half of stance during peak force production (ie, during controlled lowering) but did manifest in rectus femoris muscle force. We only observed significant differences between ACLR HT and ACLR PT participants for muscle force in the rectus femoris during walking and stair descent (to floor).

The SPM did not identify many regions of stance where muscle forces in the hamstrings were significantly different between the ACLR HT participants, ACLR PT participants, or control participants (Figure 4 and Supplementary Material 2 [available online]). The differences that did appear were limited to short instances within the initial loading response or push-off phases, but these differences were not consistent across the tasks. The biceps femoris was the least affected by the tasks, particularly in the more difficult stair descent task where we often found no main effect of group for both the short and long heads of the muscle (Table 2).

The gastrocnemii exhibited several key regions of stance where ACLR HT participants or ACLR PT participants displayed significantly different muscle forces than control participants (Figure 4 and Supplementary Material 2 [available online]). For example, ACLR PT participants showed significantly increased muscle forces compared with controls at moments leading up to push-off over

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Abbreviations: ACLR, anterior cruciate ligament reconstruction; BFL, biceps femoris (long head); BFS, biceps femoris (short head); HT, hamstring tendon graft; LG, lateral gastrocnemius; MG, medial gastrocnemius; PT, patellar tendon graft; RF, rectus femoris; SM, semimembranosus; SPM, statistical parametric mapping; ST, semitendinosus; VI, vastus intermedius; VL, vastus lateralis; VM, vastus medialis. Note: Numbers in bold indicate thresholds that had regions of stance phase crossing the SPM statistic.
level ground (ie, during walking and stair descent to floor); however, we saw no significant differences during peak force production. It was only during the more difficult stair descent to step task that the ACLR HT participants exhibited significant differences in gastrocnemius muscle force from controls, occurring near the peak force production within the loading phase. Notably, the ACLR PT participants exhibited significantly greater muscle forces than the ACLR HT participants during push-off when walking, but these differences did not appear during stair descent. However, the ACLR PT participants did exhibit significantly greater muscle forces during the load-acceptance phase of stair descent (to step).

**Discussion**

In this study, we used an established musculoskeletal modeling approach to understand how the estimates of knee muscle forces differ between individuals with ACL reconstruction with different graft types (HT and PT autograft) and “healthy” controls when performing tasks with increasing locomotor task difficulty. The principal findings of this study are: (1) individuals with an ACL reconstruction exhibit graft-specific differences in knee muscle forces when compared with control participants, (2) stair descent tasks exacerbate the differences observed during overground walking and could better discriminate changes in quadriceps and
gastrocnemii muscle forces in participants with an ACL reconstruction (ACLR HT or ACLR PT) from controls, and (3) changes in quadriceps muscle forces after a PT graft and changes in gastrocnemii muscle forces after a HT graft were only revealed during stair descent, indicating that difficult tasks, such as the stair descent tasks, can help identify biomechanical differences that were not typically detected during overground walking.

Our results support our overarching hypothesis that locomotor task difficulty is a primary driver of differences between individuals with an ACL reconstruction and healthy controls in knee muscle force production. In this study, we increased the task difficulty through the vertical height traversed during locomotion (ie, flat walking = no change, stair descent to the floor = change of 1 stair riser unit, stair descent to another step = change of 2 stair riser units). The stair descent to step task also enforced an additional constraint by the tread depth of the stairs. We found that knee forces greatly differed between ACLR HT and healthy controls, as well as between ACLR PT and healthy controls. This finding is consistent with prior studies that have shown that increasing task difficulty exacerbates the differences in knee biomechanics for individuals with an ACL reconstruction.7,26,27 Interestingly, biomechanical changes observed during a difficult task (eg, stair climbing)

Figure 4 — Hamstrings muscle force estimates during walking and stair descent for participants with an ACL reconstruction with a ACLR HT, participants with a ACLR PT, and control participants. Muscle forces are plotted as group mean forces during stance. Significance bars denote regions of stance with significant differences between groups, found using statistical parametric mapping and Bonferroni adjusted P values. ACL indicates acute anterior cruciate ligament; ACLR HT, ACL reconstruction hamstring tendon graft; ACLR PT, ACL reconstruction patellar tendon graft.*p ≤ .017. **p ≤ .001.
have been linked to patient-reported outcomes for individuals with ACL reconstruction.40 Hence, we encourage future studies to examine potential differential effects in muscle force by increasing the difficulty in a variety of tasks, which may serve as useful clinical tools to better detect residual force deficits and track recovery. Our results are promising given that even relatively simple increases to task difficulty have the potential to better differentiate muscle forces based on graft type, which may guide the development of postsurgical rehabilitation strategies to target muscles most affected by a specific type of ACL reconstruction. Altered muscle activation patterns can persist even after physical rehabilitation or postsurgery.41–44 Given the task- and graft-specific differences in joint mechanics detected in this study, care should be taken during the rehabilitation process to mitigate these persistent changes.

Because muscle forces are difficult to measure in vivo,45–47 and EMG measurements provide a poor proxy for muscle force production,48 musculoskeletal modeling has emerged as a popular method to estimate internal muscle forces.49–52 However, musculoskeletal models to explore muscle force patterns in the context of knee-related pathologies have remained limited, mostly due to the computational burden required to describe the inherent variability within clinical populations.53–55 Given the necessary assumptions made during modeling, interpretation of musculoskeletal simulations must be approached thoughtfully.56–58 Nonetheless, the results are encouraging considering the consistent patterns in estimated muscle force production related to ACLR graft type, predominantly in the quadriceps. Our results provide new evidence supporting the notion of graft-specific changes in muscle force after an ACL reconstruction, and that many of these changes are task specific.

Our finding that quadriceps muscle force is reduced in participants with an ACL reconstruction is well aligned with past studies on ACL injury.59–62 However, our work extends this idea by providing evidence that ACLR graft type also contributes to the differences in quadriceps strength. For example, we found the effect of a PT graft ACL reconstruction on the quadriceps force was task-specific, with no significant changes observed during walking as compared with controls but were revealed during the more difficult stair descent task. Past studies showing deficits in quadriceps strength often look at changes in the maximum isometric/isokinetic extension torque, 59 but it is unclear how these differences translate to changes in torque production during functional tasks such as walking and stairs descent where submaximal forces are required. Our findings suggest that group differences in muscle force during functional tasks at submaximal activation may be dependent on both the specific graft type used in the reconstruction as well as the difficulty of the functional task, and thus, researchers should consider both factors in assessments of muscle force.

Stair descent did not differentiate consistent changes in hamstring muscle forces between the ACLR HT participants and controls or ACLR PT participants and controls. These findings suggest that the role of the hamstring muscles as an agonist to the ACL63,64 has not been affected by the surgical design using a PT or HT graft. However, when considered in conjunction with our findings of a decreased force in the quadriceps muscle group, the invariant levels of peak force in the hamstring muscles during

Figure 5 — Gastrocnemii muscle force estimates during walking and stair descent for participants with an ACL reconstruction with a ACLR HT, participants with a ACLR PT, and control participants. Muscle forces are plotted as group mean forces during stance. Significance bars denote regions of stance with significant differences between groups, found using statistical parametric mapping and Bonferroni adjusted P values. ACL indicates acute anterior cruciate ligament; ACLR HT, ACL reconstruction hamstring tendon graft; ACLR PT, ACL reconstruction patellar tendon graft. *p ≤ .017. **p ≤ .001.
the loading phase may have an adverse net effect on posterior tibial translation.\textsuperscript{65} It has been suggested that the protective mechanism for the ACL employed by the hamstring may lead to an increase in the patellofemoral contact force,\textsuperscript{66} an effect that would be attenuated with reduced quadriceps muscle forces. These interpretations are consistent with the clinical observations associating anterior knee pain, a proxy to increased patellofemoral contact forces, following PT graft ACL reconstruction surgeries.\textsuperscript{67}

Although we saw no consistent patterns in hamstring muscle forces across the tasks, the majority of the differences observed were in individuals with a HT graft. For example, we saw a general reduction in the peak force in the semimembranosus during the load acceptance phase of the difficult stair descent task. However, observations of the HT group may have been confounded by methodological assumptions neglecting potential surgery-mediated changes in the semitendinosus structure, muscle volume, and tendon architecture.\textsuperscript{68} Nevertheless, the generalized reduction in force-generating capacity of the hamstrings has been reported under constraint conditions post HT reconstructive surgery.\textsuperscript{69} The exact mechanism is yet unclear and needs to be further studied.\textsuperscript{70}

Relatively few studies have examined the response of the gastrocnemius following ACL reconstruction, despite its role as a knee flexor. Fleming and colleagues\textsuperscript{80} indicated that, although in the posterior compartment, the gastrocnemius serves as an antagonist to the ACL. They further argued that the strain in the ACL increases with gastrocnemius contraction in isolation and increases with co-contraction of the quadriceps or hamstring muscle group throughout the range of flexion angles common during walking and stair descent. In the current study, the force production of the gastrocnemius was influenced by graft type. Specifically, an increase in both medial and lateral gastrocnemius force in the ACLR limbs relative to controls was detected in the PT group during the early loading phase of stair descent to another step. Combined with the concurrent reduction in quadriceps forces, the increase in the gastrocnemius force may lead to a progressive increase in the ACL strain. To this end, incorporating these changes into a model of the human knee may provide insights into the potential effect of these changes in muscle force production on the internal joint mechanics.

Given the similarity in outcomes during walking between ACL-reconstructed individuals and healthy controls, this study highlights the need to examine more functionally challenging tasks during activities of daily living (eg, stair descent) when assessing postsurgical rehabilitation outcomes. Indeed, incorporating the more biomechanically demanding task of stair locomotion revealed that ACL reconstruction with a PT graft may have a more targeted effect on the function of the quadriceps muscles, whereas ACL reconstruction using a HT graft has a more global effect on both the knee extensors and flexors. Thus, the design of a rehabilitation regimen for an individual with an autograft ACL reconstruction should consider the unique contributions of the type of graft used for replacement.

The results of the current study must be interpreted in the context of its limitations. The relatively small number of subjects could have limited our ability to detect statistically significant differences between groups in certain cases. The adaptations in the nonreconstructed legs were not evaluated as a part of this study. One might expect changes to the force production in the contralateral knee muscles to be more subtle relative to healthy controls than changes in the reconstructed limbs. Also, in the current study, the muscle properties (eg, maximum isometric force, tendon slack length) of the musculoskeletal model were not altered to account for postsurgical changes in the ACLR HT and ACLR PT patients. Given the lack of experimental data to guide such changes, we maintained the properties at the same levels as healthy individuals, thus confining our analysis to the effect of changes in movement patterns and external loading environment between healthy controls and ACLR HT and ACLR PT patients. However, we anticipate that our results are more conservative and the incorporation of postsurgical alterations in muscle properties would exaggerate the reductions in knee muscle forces observed in individuals with an ACL reconstruction. Future work should include a detailed sensitivity analysis to analyze the differential contribution of changes in normative muscle properties to muscle force estimation under pathological conditions.

In conclusion, this study found that knee muscle forces are typically reduced after ACL reconstruction and that increasing locomotor task difficulty can better differentiate estimates of knee muscle forces between healthy control participants and ACLR individuals with different graft types. Postsurgical rehabilitation strategies employ a variety of dynamic tasks aimed at restoring knee joint loading,\textsuperscript{17} and our results highlight the importance of targeted therapy to reduce the muscle force differences after ACL reconstruction. This research also emphasizes the utility of increasing task difficulty to further detect residual deficits in muscle force after an ACL reconstruction, which may provide an important clinical metric of recovery before returning athletes to play.

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