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Grip strength, muscle soreness and pain threshold perception evolution in baseball pitchers in a simulated 75-pitch game: a repeated measures study

Mathieu Tremblay ,[1,2] Samuel Anderson Sirois,[1,2] Jacques Abboud,[1,2] Martin Descarreaux [1,2]

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[1]Human Kinetics, Université du Québec à Trois-Rivières, Trois-Rivières, Québec, Canada
[2]Groupe de Recherche sur les Affections Neuromusculosquelettiques - GRAN, Université du Québec à Trois-Rivières, Trois-Rivières, Québec, Canada

Correspondence to
Mathieu Tremblay;
Mathieu.Tremblay2@uqtr.ca

ABSTRACT

Background/aim In baseball pitching, neuromuscular fatigue and its manifestations on muscle strength, muscle soreness and pain perception affect pitching performance. The purpose of this study was to quantify the evolution of grip strength, muscle soreness and pain threshold perception and pitching velocity in baseball pitchers throughout a simulated 75-pitch game.

Methods 30 high-level amateur male baseball pitchers were recruited. Repeated measure analysis of covariance with age as a covariate (p<0.05) was used to identify significant differences across blocks of pitches for grip strength, muscle soreness, pain threshold perception and pitching velocity.

Results Dominant arm grip strength (55.67±12.32 kg to 48.62±12.25 kg ; −12.66%) and pitching velocity (119.87±8.00 km/hour to 118.75±6.90 km/hour ; −0.93%) declined while muscle soreness perception increased in dominant arm forearm flexors (1.65±1.16 to 4.19±2.02 ; 25.38%), biceps (1.81±1.39 to 4.31±1.85 ; 25%) and non-dominant arm forearm flexors (1.38±1.10 to 2.12±1.63 ; 7.31%) across the pitching blocks (p<0.05).

Conclusion In summary, a pitch count of 75 fastball pitches triggered an acute decline in grip strength combined with an increase in muscle soreness perception of the throwing arm in baseball pitchers.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Pitch count and pitching velocity are commonly used as a metric to measure baseball pitcher's workload and prevent injuries.
⇒ Most injuries in baseball pitchers occur in the upper limb, especially in the forearm, elbow and shoulder region.

WHAT THIS STUDY ADDS

⇒ Grip strength assessment seems more relevant than pitching velocity for assessing acute muscle fatigue in baseball pitchers.
⇒ The forearm flexors and biceps muscles exhibit the most significant increase in muscle soreness perception with increased pitch count, compared with shoulder muscles such as the anterior deltoid and upper trapezius.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ Given the high prevalence and recent increases in upper limb injuries in baseball pitchers, this study highlights the importance of using new tools, such as grip strength assessments and muscle soreness perception scales to evaluate acute workloads. Such tools can provide a more accurate and real-time assessment of the pitcher's acute workload beyond pitch count to prevent overuse injuries. Adding these tools could help coaches and sports medicine specialists make better-informed decisions regarding pitchers' utilisation and potentially prevent pitching-related injuries.

INTRODUCTION

Baseball pitching is a complex overhead throwing skill that places significant mechanical stress on the pitcher's upper limbs and lower limbs simultaneously, which is repeated numerous times in games and training sessions.[1–3] Consequently, baseball pitchers are at great risk of developing upper limb injuries at the elbow and shoulder regions because of the high forces generated on these upper-body parts with increased throwing volume.[3] For instance, from 2016 to 2020 in professional baseball players of the Major League of Baseball, 1609 out of 3512 injuries documented were upper limb injuries at the elbow or shoulder region.[4] Muscle strains were the most documented type of injuries, and compared with other positions, pitchers had higher injury rates at the forearm, elbow and shoulder region.[4] In male college baseball pitchers, from 2014 to 2015 through 2018–2019, it was reported that the most injured body parts were the shoulder, arm or elbow.[5] In youth pitchers, it was shown that the incidence and prevalence of elbow pain were 12% and 58% as well as 17% and 35% for shoulder pain.[6]

Before developing into injuries, the pitching motion repetitions can lead to acute manifestation and accumulation of neuromuscular fatigue (NF) in the pitchers' throwing arm. NF is defined as an exercise-induced decrease in a muscle or muscle group's capacity to produce power or strength accompanied with perturbation of the sensorimotor function such as sensations of pain, discomfort and increased perception of effort.[7] The onset of NF is task-dependent, influenced by the type, intensity, duration and repetition of the motor task.[4] It results from the combination of central and peripheral mechanisms that disrupt the nervous system's ability to maintain motor performance.[7 8] In baseball, pitch count is commonly tracked by coaches during games and training sessions to measure a pitcher's level of fatigue and workload to prevent injuries associated with increased throwing volume.[9] Recent evidence suggests that relying solely on pitch count may underestimate the true load placed on the pitcher because most of the time, only pitches done in a game are accounted for and pitches done during warm-up or in preparation are not, highlighting the need for additional methods to objectively assess workload more accurately at this position to improve coaches and sport medicine specialists' decision-making regarding pitchers' utilisation.[10–12]

In younger pitchers, it was shown that pitching with fatigue is associated with greater risk of developing upper limb injuries[13] and that perception of arm soreness should be monitored and considered as a marker of fatigue during pitching.[14] Overall, NF while pitching seems to manifest through increased muscle soreness and pain perception, probably because of the high eccentric muscle activity of the elbow and shoulder of the throwing arm during the acceleration and deceleration phase of pitching, leading to decreased sensorimotor function as well as decreased shoulder and elbow range of motion.[15 16] Both acute and chronic upper limb muscle strength were also shown to decline after pitching and over the course of a season in pitchers.[17–19]

Pitching velocity and grip strength are both associated with pitching performance and are potential variables that can be used to objectively assess in real-time, alongside pitch count, the decline in upper limb muscle strength while pitching during a game.[20 21] Moreover, grip strength has been found to be associated with shoulder rotator cuff strength,[20] important muscles involved in the pitching motion.[21] In fact, a recent study by Erickson *et al*[22] highlighted the need for further knowledge regarding the changes in grip strength between innings to determine if acute changes in grip strength play a role in injury and if a threshold can be established to make decisions about removing a player from a game.[22]

Regarding muscle soreness and pain perception, a recent systematic review investigated the associations between NF, kinematic changes, performance changes, pain and injury.[23] The review results found only a few studies investigating muscle soreness and pain perception in baseball pitchers with increased pitch count.[23] To our knowledge, no study has investigated the evolution of NF and pain threshold perception during repetitive pitching in baseball pitchers.

Consequently, it seems relevant to better understand how grip strength as well as muscle soreness and pain perception at the forearm, elbow and shoulder regions evolve during repetitive pitching. Therefore, the purpose of this study is to quantify the evolution of grip strength, muscle soreness, pain threshold perception as well as pitching velocity in baseball pitchers over a 75-pitch fastball session. Given the evidence suggesting that the repetitive throwing action induces NF and decline in pitching performance, it was hypothesised that grip strength, pain threshold perception and pitching velocity measures would decrease during repetitive throwing, whereas muscle soreness would increase.

METHODS

Experimental approach

To meet the purpose of this study, a repeated measures design was used to quantify the evolution of grip strength, muscle soreness and pain threshold perception and pitching velocity. Pitchers performed a simulated 75-fastball pitch game divided into 5 blocks of 15 pitches. Pitchers were instructed to aim at the centre of the target placed behind home plate and throw as hard as possible. The number of pitches was chosen based on the Baseball Quebec federation recommendations for safe number of pitches allowed in a single day in the 13U age category,[24] considering the inclusion of pitchers from 13U and older categories. Prior to the pitching session, pitchers were asked to follow their usual dynamic body warm-up and throwing routine.

Subjects

Male amateur baseball pitchers (n=30; age: 21.43±8.86 (13–50)) volunteered to participate in this study during the off-season. A priori power analysis was conducted for the primary outcome, grip strength, using repeated measures analysis of covariance (rANCOVA). The analysis was conducted using a one-tailed alpha level of 0.05, a statistical power of 0.90 and a moderate effect size (d=0.625) and assumed an expected 10% reduction in grip strength between the first and last testing block of pitches. A minimal sample of 24 pitchers was required. To be included in this study, pitchers had to have played at least a complete season of organised baseball at the highest amateur level in their age group in the province of Quebec, Canada. Pitchers had to identify pitcher as the primary or one of their playing positions, be injury-free for the last 6 months and able to participate in baseball-related activities without any restrictions. Pitchers who reported injury or pain at the time of screening or while doing the experiment were excluded from the study. A sociodemographic questionnaire describing the self-reported player's profile was completed by pitchers and their parents or tutors if they were under 16 years of age, or by the athletes if they were over 16 years old before

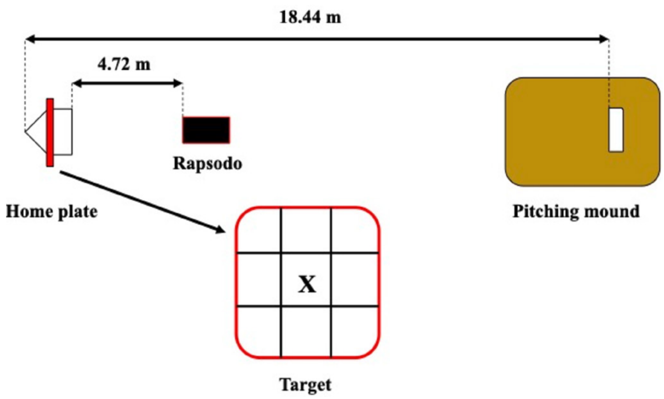

Figure 1 Schematic experimental setup.

experimentation. Pitchers and their parents or tutors (if under 16 years old) were informed of the risks and benefits before providing their written informed consent to participate in the study.

Procedures

Before each pitching session, the evaluators calibrated the centre of the target (the centre pocket of the target) with the Rapsodo Pitching V.2.0 system (Rapsodo, St. Louis, Missouri, USA) used to measure pitching performance and validate that the centre pocket of the target was also the centre of the target displayed on the Rapsodo system application to assure its calibration. Before the first block of pitches, pitchers' sociodemographic questionnaire and anthropometric data were collected. Between blocks of pitches, 5 min of rest were allowed. While resting, other measurements were collected according to the following sequence and were always taken first on the pitcher's dominant throwing arm: (1) grip strength assessment, (2) pressure pain threshold assessment and (3) muscle soreness perception. The sessions took place from September 2021 to March 2022 and from September 2022 to November 2022 during the athletes' off-season. All testing was conducted at the same facility and all pitchers pitched from a turf pitching mound positioned 18.44 m from the home plate. The target consisted of a net divided by nine pockets (Pitcher's Target Pocket Pro, Prostock Athletic Supply 2023) positioned over the home plate (figure 1). Evaluators were professional kinesiologists or kinesiology students trained for various experimental tasks and assessments before the start of the study. They retained their designated assessments until the project was finished.

Anthropometric measurements

Height and weight

The height was determined using a SECA 213 mobile stadiometer (SECA, Hamburg, Germany) that was positioned on a flat surface against a wall. Pitchers were asked to stand barefoot on the device and height was recorded to the nearest 0.1 cm.[25] Body weight was measured using a portable SECA 876 scale which was positioned on a solid floor. Pitchers were asked to step on the scale without shoes, and the weight was recorded to the nearest 0.1 kg.[25]

Grip strength, muscle soreness and pain threshold perception

Grip strength

Grip strength assessment was used to assess pitchers' upper limb neuromuscular function. This assessment is also a known factor associated with pitchers' velocity in different age groups.[26 27] Grip strength was assessed twice on each arm (the dominant and non-dominant throwing arm) and measures were taken before, between blocks of pitches and after the pitching session with a Jamar Dynamometer (JAMAR, Warrenville, USA).[28] To test grip strength, pitchers were asked to stand with the shoulder adducted and neutrally rotated, elbow fully extended and the forearm in neutral position, and to hold and squeeze the dynamometer as hard as possible for three seconds, alternating arms between measures.[29] Mean grip strength in kilograms, on both left and right arms (before beginning the session, between pitching blocks and at the conclusion of the pitching session), was used for statistical analysis.

Pressure pain threshold

Pressure pain threshold was assessed using a hand-held algometer Model 01163 Lafayette Instrument Company (Lafayette, USA) with a 12 mm diameter circular tip probe. Other studies assessing pressure pain threshold have also used this instrument.[30 31] Before experimentation, the targeted muscle bellies were identified through palpation on the pitchers' arms and marked to ensure reliability within the different testing blocks. These muscle sites were the forearm flexors (flexor-pronator muscles region), the biceps, the anterior deltoid and the upper trapezius muscles on the dominant and non-dominant throwing arm sides. The same evaluator throughout the study applied a steady and progressive pressure on these muscle sites. Measures were taken twice on each muscle site before, between blocks of pitches and after the pitching session. Mailloux *et al*[32] studied within-session test–retest reliability of pressure pain threshold in different muscle sites, in healthy subjects, and found that two measures have excellent relative reliability (ICC for the forearm flexors CI 95% 0.88 (0.74 o 0.95)).[32] Standardised verbal instructions given to the pitchers were the same as those provided in the Mailloux *et al*'s[32] study and were as follows: "This is a test of your sensitivity to deep pain. I will press this algometer against your forearm flexors/biceps/anterior deltoid/upper trapezius and will gradually increase the pressure. Please say 'Now' as soon as the pressure starts to be painful. Remember that this is not a pain tolerance test, it is a pain threshold test". The mean of the two measures for each muscle site in kilograms taken before, between blocks of pitches, and after the pitching session was used for statistical analysis.

Muscle soreness perception

Muscle soreness perception intensity was expressed once verbally by the pitchers according to a modified Visual Analogue Scale of 0–10[33] on the same muscle sites as pressure pain threshold measures, that is, forearm flexors, biceps, anterior deltoid and upper trapezius muscles on the dominant and non-dominant throwing arm sides. Measures were expressed before, between blocks of pitches and after the pitching session. Perceived muscle soreness intensity expressed before, between blocks of pitches and after the pitching session was used for statistical analysis.

Pitching velocity

The Rapsodo V.2.0 system was used to measure ball velocity with each pitch. The Rapsodo system, a monocular camera-based system, was positioned 4.72 m in front of home plate on the ground facing the pitcher. This technology has been used in recent studies to assess pitchers' performances.[27 34 35] Pitchers used a standard 141.75 g baseball to perform the pitching session. Pitchers were free to throw from a stretch or wind-up position but were asked to remain consistent with delivery throughout the protocol. Pitching velocity was measured in miles per hour described as the release speed of the ball as the ball leaves the pitcher's fingers. Pitching velocity is often used to assess muscle fatigue in pitchers.[23] The mean velocity of the 15 pitches for each block was used for statistical analysis.

Statistical analysis

Descriptive data including mean±SD of pitchers' characteristics and assessments were calculated. Normal distribution for studied variables was assessed using the Shapiro-Wilk test and visual inspection. An rANCOVA with effect size (partial eta squared η_p^2) was performed to identify differences between pitching blocks for all studied variables with age as a covariate, where η_p^2=0.01 indicated small effect, η_p^2=0.06 indicated medium effect, and η_p^2=0.14 indicated large effect. Planned polynomial contrast analyses were used to assess trends in studied variables across experimentation. The Greenhouse-Geisser adjustment was used whenever assumptions of sphericity were not met. The significance levels for all analyses were set to p<0.05. Analyses were performed on available data from athletes that completed the protocol. Statistical computations were performed using IBM SPSS Statistics V.28.0.0 (Microsoft, Armonk, USA).

RESULTS

Pitchers' descriptive profile describing their age, height, body weight as well as their playing experience are presented in table 1. Four pitchers did not complete the protocol because of exhaustion or significant feelings of muscle soreness, whereas the data of one pitcher were incomplete because of technical problems and data synchronisation default (pressure pain threshold and Rapsodo V.2.0).

Table 1 Pitchers' descriptive profile

	N	Mean	SD
Age (years)	30	21.43	8.86
Height (cm)	30	179.17	8.44
Weight (kg)	30	79.20	12.73
Years of experience playing organised baseball	27	13.48	7.40
Participation in school-related year-round baseball programme (%)	N 28	Yes 53	No 47
Dominant arm			
Right-handed pitcher	25		
Left-handed pitcher	5		

Results of rANCOVA for grip strength, muscle soreness and pain threshold perception measures showed a main significant decrease across pitching blocks for dominant arm grip strength (F (5)=10.246; p<0.001; η_p^2=0.299) as well as an increase for perceived muscle soreness in forearm flexors (F (5)=4.827; p=0.005; η_p^2=0.167) and biceps (F (5)=3.030; p<0.045; η_p^2=0.112) of the dominant throwing arm and in the forearm flexors (F (5)=5.491; p=0.003; η_p^2=0.186) of the non-dominant arm. No difference was found for non-dominant arm grip strength, muscle soreness perception in the anterior deltoid and upper trapezius of the dominant arm and in the biceps, anterior deltoid and upper trapezius of the non-dominant arm. Also, no difference was found in the pressure pain threshold assessments in the dominant and non-dominant arms in assessed muscle sites. No age effect was found for grip strength, muscle soreness and pain threshold perception measures across pitching blocks. Results for grip strength, muscle soreness and pain threshold perception are presented in table 2.

Figure 2 presents dominant arm grip strength evolution across pitching blocks and figure 3 perceives muscle soreness evolution of the pitchers' dominant arm across pitching blocks per muscle sites.

Results of rANCOVA for pitching velocity showed main significant differences characterised by a decline in pitching velocity (F^4=3.701; p=0.039; η_p^2=0.142) across pitching blocks. No age effect was found for pitching velocity across pitching blocks. Results for pitching velocity measures are presented in table 3.

Planned polynomial contrasts analysis revealed significant negative linear trends for grip strength in both the dominant (p<0.001) and non-dominant arm (p=0.029) and pitching velocity (p=0.037). Positive linear trends were revealed for muscle soreness perception in the forearm flexors in both the dominant (p<0.009) and non-dominant arms (p<0.016).

DISCUSSION

The purpose of the study was to quantify the evolution of grip strength, muscle soreness and pain threshold

Table 2 Results of grip strength, muscle soreness and pain threshold perception across blocks

Neuromuscular fatigue and associated measures*	N	Pre	Block 1	Block 2	Block 3	Block 4	Block 5	% Blocks 1–5	rANCOVAs p<0.05
Grip strength dominant (kg)	26	55.67±12.32	53.02±12.22	51.83±12.56	50.77±12.27	49.83±12.92	48.62±12.25	↓12.66 %	<0.001†
Grip strength non-dominant (kg)	26	53.81±12.08	51.81±11.67	51.67±11.16	51.40±11.16	50.89±12.44	49.94±11.86	↓ 7.19%	0.073
PMS flexors dominant (0–10)	26	1.65±1.16	2.38±1.30	2.73±1.51	3.15±1.71	3.92±1.83	4.19±2.02	↑ 25.38%	0.005†
PMS biceps dominant (0–10)	26	1.81±1.39	2.27±1.25	2.73±1.37	3.77±1.51	3.96±1.71	4.31±1.85	↑ 25.00%	0.045†
PMS ant. delt dominant (0–10)	26	2.19±1.65	2.19±1.30	2.69±1.41	3.04±1.45	3.50±1.53	3.69±1.74	↑15.00%	0.102
PMS upper. trap dominant (0–10)	26	2.19±1.74	2.31±1.67	2.35±1.72	2.96±1.93	3.35±1.94	3.38±2.16	↑ 11.92%	0.170
PMS flexors non-dominant (0–10)	26	1.38±1.10	1.46±0.99	1.50±0.99	1.65±1.16	1.92±1.35	2.12±1.63	↑ 7.31%	0.003†
PMS biceps non-dominant (0–10)	26	1.31±1.26	1.62±1.36	1.85±1.74	2.00±1.41	2.27±1.49	2.42±1.68	↑ 11.15%	0.360
PMS ant. delt non-dominant (0–10)	26	1.54±1.45	1.73±1.22	1.92±1.29	1.96±1.15	2.15±1.46	2.38±1.79	↑ 8.46%	0.385
PMS upper. trap non-dominant (0–10)	26	2.15±1.77	2.08±1.74	2.12±1.77	2.31±1.67	2.65±1.94	2.65±1.94	↑ 5.00 %	0.289
PPT flexors dominant (kg)	25	8.19±3.19	8.16±3.45	7.93±3.35	7.76±3.08	7.82±3.06	7.59±2.96	↓7.33%	0.060
PPT biceps dominant (kg)	25	6.32±2.59	6.50±2.50	6.60±2.85	6.65±3.17	6.43±2.87	6.17±2.72	↓ 2.37%	0.336
PPT ant. delt dominant (kg)	25	7.64±3.30	7.80±3.46	7.81±3.69	7.91±3.46	7.91±3.26	7.83±3.47	↑ 2.49%	0.136
PPT upper. trap dominant (kg)	25	8.86±3.97	9.02±4.06	9.25±4.50	8.77±3.94	9.31±4.05	9.19±4.28	↑ 3.72%	0.088
PPT flexors non-dominant (kg)	25	8.48±3.47	8.66±3.68	9.03±3.90	8.67±3.66	8.64±3.51	8.69±3.53	↑ 2.48%	0.104
PPT biceps non-dominant (kg)	25	6.14±2.33	6.10±2.50	6.40±2.95	6.33±2.82	6.31±2.69	6.30±2.88	↑ 2.61%	0.203
PPT ant. delt non-dominant (kg)	25	6.83±2.71	7.33±3.13	7.44±3.44	7.24±3.06	7.14±3.33	7.32±3.61	↑ 7.17%	0.248
PPT upper. trap non-dominant (kg)	25	9.47±4.08	9.12±4.14	9.43±3.90	9.61±4.41	9.59±4.06	9.28±3.99	↓ 2.00%	0.105

*Data are presented as mean±SD.
†Significant results p<0.05.
PMS, perceived muscle soreness; PPT, pressure point threshold; rANCOVAs, repeated measure analysis of covariance.

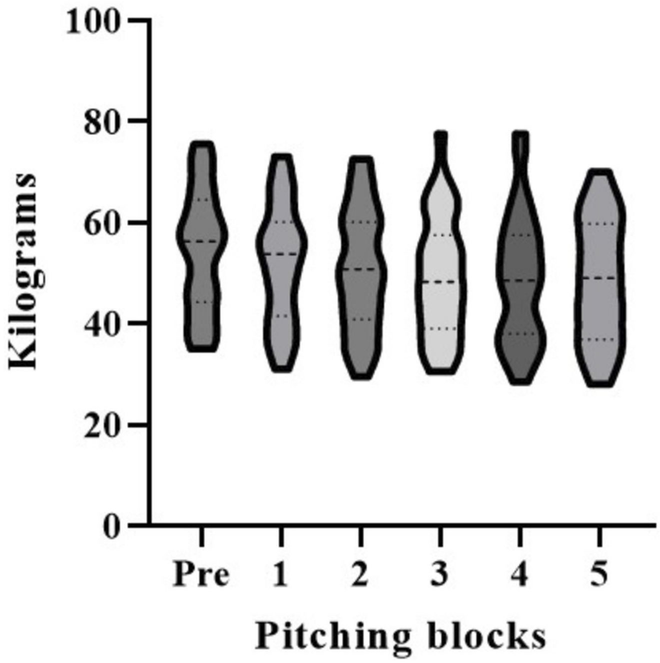

Figure 2 Dominant arm grip strength evolution across pitching blocks. The middle dotted line represents the mean grip strength across blocks. The lower and upper dotted line represent the 1st and 3rd quartile. The violin boxes represent the data distribution density for each pitching blocks.

perception and pitching velocity in baseball pitchers throughout a simulated 75 fastball pitches game. The results showed that, with an increase in pitches thrown throughout the pitching blocks, a significant decrease with moderate to large effect size of the dominant arm grip strength and pitching velocity was found in pitchers. An increase with moderate to large effect size was also identified in our sample for muscle soreness perception measures of the dominant arm forearm flexors and biceps and for the non-dominant arm forearm flexors. Pitching velocity significantly decreased from block 1 to block 5 by 0.93% which represents a small decrease when considering game-related performances. Scientific evidence regarding decreases in pitching velocity linked to NF is heterogeneous. Erickson *et al*[36] and Escamilla *et al*[37] also reported a small but significant decrease in pitching velocity in their respective studies investigating kinematics and kinetics changes throughout a simulated game and the impact of fatigue on pitching mechanics in younger male adolescents.[36,37] In contrast, Dale *et al*[1] study showed a small yet not significant decrease in pitching velocity in their protocol of 60 full effort pitches divided into innings of 15 pitches.[1] Pitching velocity is a key performance indicator strongly linked to better performance against batters, such as higher strikeout rate, fewer walks, fewer hit-by-pitches and fewer home runs allowed.[26,38] Maintaining high pitching velocity is crucial for pitchers to remain competitive against batters, considering that a decrease in velocity during pitch repetition can benefit batters by improving their decision-making and increasing the chance of making contact with the ball.[39] Thus, a decline in pitching velocity gives batters more time to react. To our knowledge, it is still unclear how much of a velocity decline in pitching is needed to increase the batter's chance of getting a hit.

In the present study, along with pitching velocity, grip strength assessment was used to monitor NF across the pitching blocks. Being a factor associated with pitching velocity in different population and age groups,[26,27,40] grip strength assessment reflects mostly the isometric strength and contraction of the forearm muscles. A significant

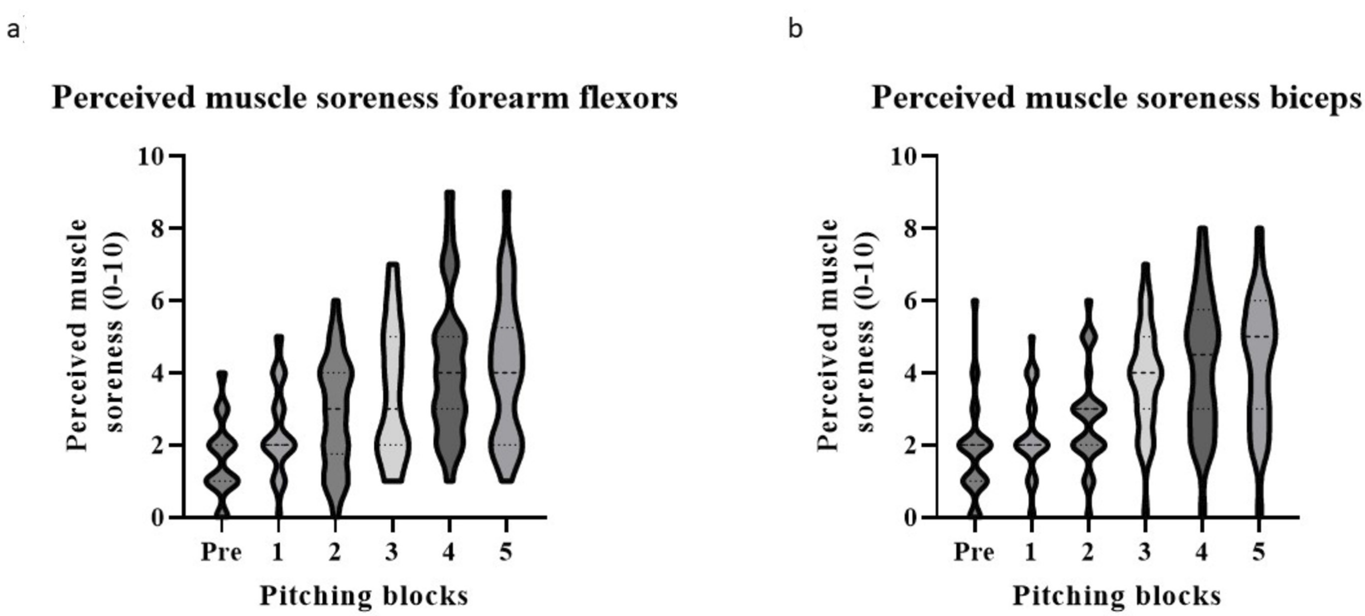

Figure 3 Dominant arm muscle soreness perception measures evolution per muscle sites. The middle dotted line represents the mean PMS across blocks. The lower and upper dotted line represent the 1st and 3rd quartile. The violin boxes represent the data distribution density for each pitching blocks.

Table 3 Results of pitching velocity across blocks

Pitching velocity*								
	N	**Block 1**	**Block 2**	**Block 3**	**Block 4**	**Block 5**	**% Blocks 1–5**	**rANCOVA p<0.05**
Pitching velocity (km/hour)	26	119.87±8.00	120.35±7.60	119.76±7.12	119.26±6.96	118.75±6.90	↓ 0.93%	0.039†

*Data are presented as mean±SD.
†Significant results p<0.05.
rANCOVA, repeated measure analysis of covariance.

decrease of 12.66% (55.67 kg±12.32 to 48.62 kg±12.25) of the dominant arm grip strength in this study shows that grip strength should be considered as a complementary measure to pitching velocity to assess pitchers' muscle fatigue in games or practices. For example, assessment of grip strength could be done in games between innings or before and after a practice on the pitcher's dominant arm to assess pitchers' acute workload. Grip strength is an easy, inexpensive physical assessment and tool that can be used by sports medicine specialists or coaches in practical settings or games to monitor muscle fatigue induced by repetitive throwing and to manage game decisions related to the athletes' performance and risk of upper extremity overuse.

In addition to a decrease in grip strength and pitching velocity, muscle soreness perception intensity of the forearm flexors for both arms and the biceps of the dominant arm increased in our sample of pitchers. These results for the dominant throwing arm are similar to our recent findings, which investigated the effects of upper and lower body NF protocols on baseball pitchers' velocity, and also showed an increase in localised muscle soreness perception at the forearm flexors after both fatigue protocols and fastball pitches.[41] The subjective increase in muscle soreness of the non-dominant forearm flexors could be explained by the combination of the stabilising role and the weight of the glove placed on the non-throwing arm while pitching. Another hypothesis involves the contralateral strength training effect, where training one side of the body also affects the other side to a lesser extent.[42] In the context of baseball pitching, the motor task performed by the throwing arm may lead to a transfer of the neural drive to the glove arm inducing similar neuromuscular adaptations.

Interestingly, pain threshold perception measured by pressure pain threshold assessment showed no difference in these same muscle sites across the pitching blocks. Yet, a close but non-significant decline was shown for the pain threshold perception assessment of the forearm flexor muscles (p=0.06; −7.33%). To our knowledge, this study is the first to assess the acute muscle soreness perception and pressure pain threshold on both the throwing dominant arm and non-dominant throwing arm across a pitching session and through several muscle sites. Acute bouts of exercise have been shown to cause exercise-induced hypoalgesia defined as a reduction in pain sensitivity when a nociceptive stimulus is present.[43] Acute physical exercise seems to increase the pain threshold and tolerance, both during and after exercise, depending on the type and intensity.[44] In their meta-analysis on the effects of acute exercise on pain perception, Naugle *et al*[45] found that intermittent and dynamic resistance-type exercises can produce moderate to high levels of exercise-induced hypoalgesia and influence pain threshold and tolerance in healthy adults.[45] Thus, the pressure pain threshold assessment does not seem to be a relevant tool to measure pitchers' acute workload within a pitching session compared with muscle soreness perception. Other studies investigating pressure pain threshold and muscle soreness perception have been mostly related to chronic pain studies and delayed-onset muscle soreness studies after exercise.[31 46 47] Future studies should investigate the associations between grip strength, muscle soreness perception and pain threshold in game settings where stakes are higher for pitchers.

Although pitching velocity significantly decreased with pitch count in this study, the decline appears practically trivial. From a motor control theory standpoint, this result could be explained by the motor synergy occurring while pitching in baseball pitchers. Motor synergy implies that multiple muscles are bound together and that a central control signal proportionally activates all muscles involved in the synergy related to task demand.[48] When task demands change, such as increasing NF, the control signal changes and triggers parallel changes in an attempt to maintain optimal performance and, therefore, maintain high pitching velocity.[48] More studies are needed to find the minimal clinically important difference in pitching velocity decline that could lead to a decrease in-game pitching performance.

Finally, despite the difference in age range across pitchers in this study, age did not seem to influence either grip strength, muscle soreness and pain threshold perception measures or pitching velocity measures, as shown by the rANCOVA results. The homogeneity of our sample in their level of play (high-level amateur) and the inclusion criteria of including players reporting pitcher as their primary or one of their playing positions suggest that younger and older pitchers behave similarly to an increase in pitch count workload. In summary, our results showed that a pitching session of 75 fastball pitches led to a decrease in pitching velocity and grip strength in the dominant throwing arm. Muscle soreness perception increased for the dominant and non-dominant throwing arms for the forearm flexors and for the dominant arm only for the biceps muscles across the pitching session. Future studies should investigate the chronic effects of repetitive pitching on grip strength, muscle soreness and pain threshold perception over time and days post pitching, such as exercise-induced muscle damage and delayed onset muscle soreness effects on repeated pitching performance and upper extremity neuromuscular function. By understanding the chronic effect of repetitive pitching on grip strength, muscle soreness and pain threshold perception, it will be easier to establish the significant amount of decline that could lead to future injuries in pitchers.

Limitations

This study is not without limitations. The indoor controlled pitching environment may not reflect outdoor and game-specific conditions where other parameters such as facing batters under the pressure of competition can influence NF development and pitching performances. Pitchers' readiness to throw a simulated game was not controlled for in the study even though we only included in the statistical analyses pitchers who were able to complete the protocol of 75 pitches in the results. Another limitation is the localised assessments of muscle soreness perception and pressure pain threshold that may not reflect overall muscle soreness perception and pain sensitivity of the upper extremity. A measure of overall arm perceived muscle soreness may have yielded different results. Also, this study did not include an objective, external evaluation, such as imaging tests of the pitcher's musculoskeletal system in response to the repetitive pitching task. This study did not directly evaluate the effects of a gradual decline in grip strength, and we were, therefore, unable to evaluate the relationship between the decrease in grip strength, muscle soreness perception and pitch count. Finally, this study required pitchers to throw only fastballs at the centre of a target and execute the same delivery through the pitching session, whereas game-specific conditions require pitchers to adapt to game situations and aim and throw different pitches to get batters out.

CLINICAL IMPLICATIONS

This study quantified the evolution of grip strength, muscle soreness and pain threshold perception as well as pitching velocity in baseball pitchers' during a 75-pitch session. It also offers new insights and tools for sports medicine specialists and coaches, enabling them to measure baseball pitchers' acute workload without relying solely on pitch count. Evaluating the decrease in grip strength and increase in muscle pain in the forearm flexors and biceps muscles due to consecutive pitching could be used as early indicators of pitchers' muscle fatigue. Both assessments require low expertise and are easy to conduct in different settings. Pain threshold perception assessment of the throwing arm may vary between baseball pitchers and more research is needed to understand its evolution in repetitive pitching sessions. Future research should assess these physiological phenomena and the possible injuries mechanisms and changes in musculoskeletal tissues that can occur repeated pitching.

X Mathieu Tremblay @MattTremblay27

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ORCID iDs
Mathieu Tremblay http://orcid.org/0000-0002-3251-8512
Martin Descarreaux http://orcid.org/0000-0002-3545-5860

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