5-14-2021

Is Decreased Trunk Flexion Angle a Contributing Factor to Patellofemoral Joint Loading in Runners with Patellofemoral Pain?

Christine DuVall
University of Nevada, Las Vegas

Zachary Clark
University of Nevada, Las Vegas

Tavin Fox
University of Nevada, Las Vegas

Caitlin Howden
University of Nevada, Las Vegas

IS DECREASED TRUNK FLEXION ANGLE A CONTRIBUTING FACTOR TO PATELLOFEMORAL JOINT LOADING IN RUNNERS WITH PATELLOFEMORAL PAIN?

By

Zachary A. Clark
Christine DuVall
Tavin Fox
Caitlin Howden

A doctoral project submitted in partial fulfillment
of the requirements for the

Doctor of Physical Therapy

Department of Physical Therapy
School of Integrated Health Sciences
Graduate College

University of Nevada, Las Vegas
May 2021

UNLV | GRADUATE COLLEGE

Doctoral Project Approval

The Graduate College
The University of Nevada, Las Vegas

May 14, 2021

This doctoral project prepared by

Zachary Clark

Christine DuVall

Tavin Fox

Caitlin Howden

entitled

Is Decreased Trunk Flexion Angle a Contributing Factor to Patellofemoral Joint Loading in Runners with Patellofemoral Pain?

is approved in partial fulfillment of the requirements for the degree of

Doctor of Physical Therapy
Department of Physical Therapy

Kai-Yu Ho, Ph.D.
Research Project Coordinator

Daniel Young, Ph.D.
Research Project Advisor

Merrill Landers, Ph.D.
Chair, Department of Physical Therapy

Kathryn Hausbeck Korgan, Ph.D.
Graduate College Interim Dean

Abstract

Purpose/Hypothesis: Reduced trunk flexion during running is theorized to be a contributing factor of elevated patellofemoral joint (PFJ) stress in runners with patellofemoral pain (PFP); thus, the primary purpose of this research study was to determine if runners with PFP would exhibit differences in PFJ stress and trunk flexion angle during running as compared to pain-free runners across three speeds. We hypothesized that runners with PFP would exhibit higher PFJ stress and decreased trunk flexion while running compared to the pain- free runners.

Number of Subjects: 7 runners with PFP and 5 similar pain-free control runners.

Materials/Methods: Kinematics and kinetics of the trunk and lower extremity were obtained at 3 different running conditions: self-selected, fast (10% faster than self-selected), and slow (10% slower than self-selected) speeds. PFJ stress, PFJ reaction force, and PFJ contact area were determined using a biomechanical model that utilized subject-specific input variables (i.e., knee flexion angle and knee extensor moment). A 2-way ANOVA with repeated measures was used to compare outcome variables across the 3 speeds and between the 2 groups.

Results: Running speeds were similar between groups. There was no statistically significant difference in peak PFJ stress between groups across the 3 speeds ($p>0.05$). Additionally, no significant difference was found in trunk flexion angle, PFJ reaction force, PFJ contact area, knee extensor moment, knee flexion angle, GRF at peak stress, PFJ contact area, knee flexion angle, or trunk flexion angle between the two groups across the 3 speeds ($p>0.05$). Peak PFJ stress was found to be highest during fast running compared to the slow speed across both groups ($p= 0.017$).

Conclusions: Runners with and without PFP exhibited similar peak PFJ stress and trunk flexion angle when running at slow, self-selected, and fast speeds on a treadmill.

Clinical Relevance: This preliminary work does not support the theory that reduced trunk flexion during running is a contributing factor leading to increased PFJ stress during running in runners with PFP when compared to pain-free runners.

Key Words: Patellofemoral pain, trunk flexion angle, running, patellofemoral joint stress

Acknowledgements

This research study was made possible by the 2019 University of Nevada, Las Vegas Physical Therapy Student Opportunity Research Grant. The authors would like to thank Kai-Yu Ho, PT, PhD and Tiffany Barrett, PT, DPT for their support and guidance throughout the completion of this project.

Table of Contents

Abstract .... *iii*

Acknowledgements .... *v*

List of Figures .... *vii*

Introduction *1*

Methods *3*

- **Participants** 3
- **Instrumentation** 4
- **Procedure** 4
- **Data Processing** 6
- **Statistical Analysis** 7

Results *8*

- **Subject Characteristics** 8
- **Peak Patellofemoral Joint Stress** 9
- **Trunk Flexion Angle** 10
- **Patellofemoral Joint Reaction Force** 11
- **Patellofemoral Joint Contact Area** 12
- **Knee Extensor Moment** 13
- **Knee Flexion Angle** 14
- **Vertical Ground Reaction Force** 14

Discussion *16*

Conclusion *19*

Appendix *20*

References *26*

Curriculum Vitae *28*

List of Figures

Figure 1. Flow chart depicting order of running trials. 6

Figure 2. Peak PFJ stress during slow, self-selected, and fast speed running in runners with PFP and pain-free control runners. 9

Figure 3. Trunk flexion angle at the time of peak PFJ stress during slow, self-selected, and fast speed running in runners with PFP and pain-free control runners 10

Figure 4. PFJ reaction force at the time of peak PFJ stress during slow, self-selected, and fast speed running in runners with PFP and pain-free control runners 11

Figure 5. PFJ contact area at the time of peak PFJ stress during slow, self-selected, and fast speed running in runners with PFP and pain-free control runners 12

Figure 6. Knee extensor moment at the time of peak PFJ stress during slow, self-selected, and fast speed running in runners with PFP and pain-free control runners. 13

Figure 7. Knee flexion angle at the time of peak PFJ stress during slow, self-selected, and fast speed running in runners with PFP and pain-free control runners 14

Figure 8. Vertical ground reaction force at the time of peak PFJ stress during slow, self-selected, and fast speed running in runners with PFP and pain-free control runners. 15

Figure 9. Medical History Questionnaire 22

Figure 10. Subject Screening Tool (filled by investigators) 23

Figure 11. GPAQ Questionnaire 24

Introduction

Patellofemoral joint pain (PFP) is the most prevalent type of injury sustained by runners and accounts for 17% of musculoskeletal injuries reported in this population (Francis, Whatman, Sheerin, Hume, & Johnson, 2019; Walter, Hart, Mcintosh, & Sutton, 1989). While the cause of PFP is thought to be multi-factorial, increased patellofemoral joint (PFJ) stress, defined as PFJ reaction force per unit of contact area, is a primary contributing factor for PFP in runners (Ho, French, Klein, & Lee, 2018).

There are several factors contributing to elevated PFJ stress during running, including decreased trunk flexion angle, reduced PFJ contact area (Ho et al., 2018), and step rate (Chumanov, Wille, Michalski, & Heiderscheit, 2012). In healthy runners, running with an upright trunk posture is associated with elevated PFJ stress and reaction forces due to an increased knee extensor moment. The increases in knee extensor moment are mainly driven by an increased knee lever arm (perpendicular distance from the axis of the knee joint to the ground reaction force vector) as the result of a posterior shift of vertical ground reaction force due to decreased trunk flexion (Ho et al., 2018).

Running speed may also be a factor in determining the PFJ loading during running. Healthy runners exhibit a greater trunk flexion angle while running at a higher speed (Fisher, Louw, Cockcroft, & Tawa, 2018). Additionally, an increased step rate from running at a fast speed reduces PFJ reaction forces during running (Lenhart, Thelen, Wille, Chumanov, & Heiderscheit, 2014). However, the effects of altered trunk posture and running speeds on PFJ loading have been primarily studied in pain-free runners. It remains unclear if runners with PFP demonstrate a decreased trunk flexion angle during running across different speeds, leading to higher PFJ stress and PFP symptoms. Thus, the primary purpose of this research study was to determine if runners with PFP would exhibit higher PFJ stress and decreased trunk flexion during running when compared to pain-free runners across various speeds. The results of this study could help to inform treatment and reduce incidence and occurrence of PFP in runners.

Methods

Participants

The sample size was estimated using a previous study that examined running with various trunk postures and changes in PFJ stress (Teng & Powers, 2014). We calculated that 17 individuals in each group would be necessary to detect a significant change in trunk flexion angle between groups, with 80% power and an α level of 0.05.

The study was approved by the Institutional Review Board of the University of Nevada, Las Vegas. Participants were recruited via word of mouth, flyers, emails, and social media in the Las Vegas area between 2019 and 2020. Once runners responded to advertisements, they were contacted by phone and/or email and scheduled for a time to come into the lab at UNLV. Runners with PFP were given the Medical History Questionnaire to fill out which included questions regarding each subject's running distances, primary sport, pregnancy status, numeric pain scale, prior knee surgery, other diagnoses of knee injuries/diseases, and history of traumatic dislocation. Subjects with PFP also underwent a physical exam, which consisted of a patella compression test and peri-patellar palpation to rule in PFP. Both the Medical History Questionnaire and physical exam were utilized to differentiate between PFP and other knee pathologies that could be causing knee pain such as patellar tendonitis or arthritis. The screening was also used to determine if the participant met any exclusion criteria.

Participants were admitted to the study if they were between 18 and 40 years old, ran at least 6 miles per week, if their knee pain originated behind the patella, and had an insidious onset of symptoms lasting longer than 3 months (Hahn et al., 2017; Ho, Hu, Colletti, & Powers, 2014). Subjects were excluded from the study if they had prior knee surgery, pain that did not come from the kneecap during screening, a history of traumatic dislocations, were pregnant or thought they may have been pregnant. To control for potential confounding from running biomechanics, we recruited pain-free runners with similar age, height, weight, and weekly mileage (<10% difference). The pain-free control group had the same inclusion and exclusion criteria as the experimental group, but no history of PFP within the last 2 years (Ho et al., 2014). Eligible participants were educated on the procedures, benefits, and risks of the study and asked to sign the informed consent form if they agreed to participate.

Instrumentation

A 12-camera motion analysis system (Vicon, Oxford Metrics Ltd., Oxford, UK) was used to capture kinematic data of the lower extremity and trunk at 250 Hz. Ground reaction forces were collected at a sampling rate of 2000 Hz using force plates instrumented in a dual-belt treadmill (Fully Instrumented Treadmill, Bertec Corp., Columbus, OH, USA) (Ho et al., 2018).

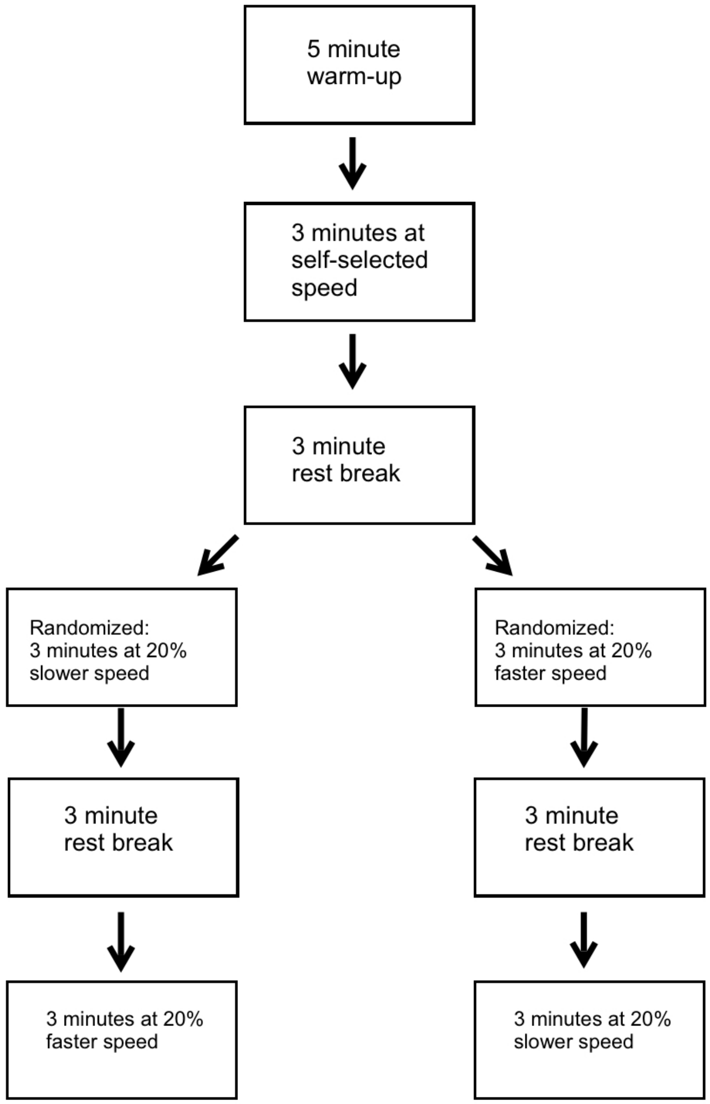
Procedure

Participants attended one 60-min session and were tested under 3 different running conditions: self-selected, faster, and slower speeds. Faster and slower speed was defined as a 20% increase or decrease in the subject's self-selected speed. Each participant was tested in self-selected speed condition first and followed by either slower or faster speed condition in an altered order. To determine the order of running conditions, a number was randomly selected by a researcher which was designated as either "slow first" or "fast first".

Participants were asked to warm-up by running at a comfortable, self-selected, speed for 5 minutes. One investigator placed markers on the upper extremity and trunk while another placed markers on the lower extremities. A 6 degree-of-freedom marker set was used in this study. This set of markers was used because it has been shown to have little error and high reliability (Collins, Ghoussayni, Ewins, & Kent, 2009; Zuk & Pezowicz, 2015). In addition, the marker set that was placed on the spine is valid in measuring trunk movements both dynamically and statically (Smith & Kulig, 2016). Individual reflective markers were placed on the following anatomical landmarks: toenail of the great toe, 1st and 5th metatarsal heads, medial and lateral malleoli, medial and lateral femoral epicondyles, L5-S1 joint space, greater trochanters, iliac crests, anterior superior iliac spines (ASIS), acromioclavicular joints, and posterior superior iliac spines (PSIS). A set of 4 reflective markers in a predetermined square layout (rigid quadrads) were placed on the bilateral heel aspect of participant's shoes and the lateral thighs. A rigid quadrad was also placed on the spinous process of T3. To set the joint axes and segmental coordinate systems, a static calibration trial was performed by having the participant stand still with arms abducted to 90 degrees. Immediately following the static calibration trial, all markers, except for the rigid quadrads and those on the iliac crests and L5-S1, were removed.

During each of the running conditions (self-selected, fast, and slow) participants ran for three minutes and three 20-second trials were collected during that time. Participants were given a 3-minute rest between each condition to avoid fatigue (Figure 1).

Figure 1. Flow chart depicting order of running trials.



Data Processing

Vicon Nexus software (Oxford Metric Ltd., Oxford, UK) was utilized to label and digitize the reflective markers used to gather the kinematic data. The ground reaction forces were normalized to participants' body mass for data analysis. The kinematics and kinetics of the trunk and lower extremities (i.e., the sagittal plane motions of the knee joint) were computed using Visual 3D software (C-Motion, Rockville, MD, USA).

A previously developed 2-dimensional PFJ model was used to estimate PFJ stress during running. The quadriceps force was estimated by dividing knee extensor moment by the quadriceps moment arm during the running trials. Next, a ratio reported by van Eijden et. al. showing a relationship between PFJ reaction force and quadriceps force as a function of knee flexion angle was used to estimate the PFJ reaction force (van Eijden, Weijs, Kouwenhoven, & Verburg, 1987). The last step of the algorithm was to calculate the PFJ stress, which was estimated by dividing PFJ reaction force by the PFJ contact area from the data of Powers et. al. (Powers, Witvrouw, Davis, & Crossley, 2017; van Eijden et al., 1987).

Statistical Analysis

The primary variables were trunk flexion angle and peak PFJ stress. The secondary variables were PFJ reaction force, PFJ contact area, and vertical ground reaction force at the time of peak PFJ stress. We compared each variable between groups across the 3 conditions using a 2 (groups: PFP and controls) X 3 (speeds: self-selected, faster, and slower) 2-way ANOVA with repeated measures. If a significant region-by-group interaction or a significant main effect was found, post hoc testing (paired *t* tests with a Bonferroni correction) was employed. All statistical analyses were performed with the use of SPSS 24.0 statistical software (International Business Machines Corp, Armonk, New York). A significant difference was defined as $p \leq 0.05$.

Results

Subject Characteristics

Due to the novel coronavirus research was temporarily suspended and in the end group size was also limited. Therefore, there were 7 runners (5 females and 2 males) in the experimental group (runners with PFP). The control group (runners without PFP) had 5 runners (3 females and 2 males). An independent samples t-test was conducted to ensure that there was no difference in the subject characteristics between the two groups of runners (PFP & pain-free controls). There was no significant difference in the mean age (p=0.901), height (p=0.647), weight (p=0.193), weekly mileage (p=0.994), and running speeds for slow, self-selected, and fast conditions (p>0.5) between the two groups (Table 1).

Table 1. Subject Characteristics

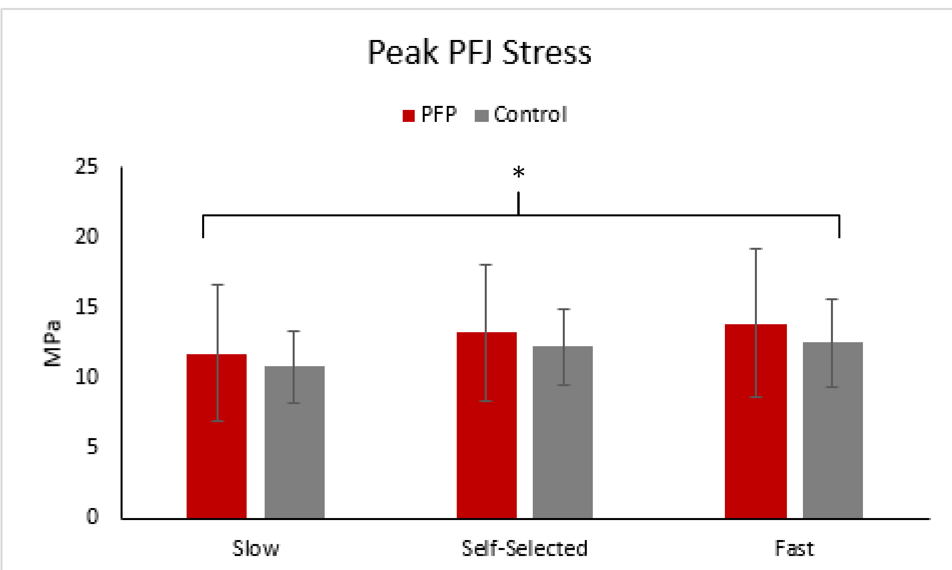
PFP: patellofemoral pain
AKPS: Anterior Knee Pain Scale
**The Anterior Knee Pain Scale (AKPS) was not given to control group participants, as the inclusion criteria required that control group participants had no knee pain to report.*

	PFP group (n=7)	Control group (n= 5)	P-value (2-tailed)
Age (years)	28.00 ± 8.23	27.40± 7.77	0.901
Height (cm)	172.72 ± 12.27	175.77± 8.87	0.647
Weight (kg)	65.19 ± 12.95	75.68 ± 12.63	0.193
Weekly mileage (miles/week)	13.57 ± 6.73	13.60± 4.72	0.994
AKPS	81.57 ± 4.89	N/A*	N/A*
History of pain (months)	25± 22.69	N/A*	N/A*
Self-selected running speed (m/s)	2.60 ± 0.55	2.53 ± 0.54	0.815
Slow running speed (m/s)	2.08 ± 0.44	2.06 ± 0.39	0.931
Fast running speed (m/s)	3.12± 0.66	2.99 ± 0.70	0.747

Peak Patellofemoral Joint Stress

Across the 3 running conditions, the peak PFJ stress occurred at approximately 38% of the stance phase for the control group and 37% of the stance phase for the PFP group. There was not a group by speed interaction (p=0.917) in peak PFJ stress. There was no main effect of group in peak PFJ stress during running (p=0.660). However, there was a statistically significant main effect of speed in peak PFJ stress (p=0.006) (Tables 2&3). In post-hoc analyses peak PFJ stress was observed to be significantly lower during slow running than at self-selected (p=0.002) and fast running (p=0.017) speeds across both groups. There was no significant difference in peak PFJ stress between fast and self-selected running conditions (p=0.435) (Figure 2).

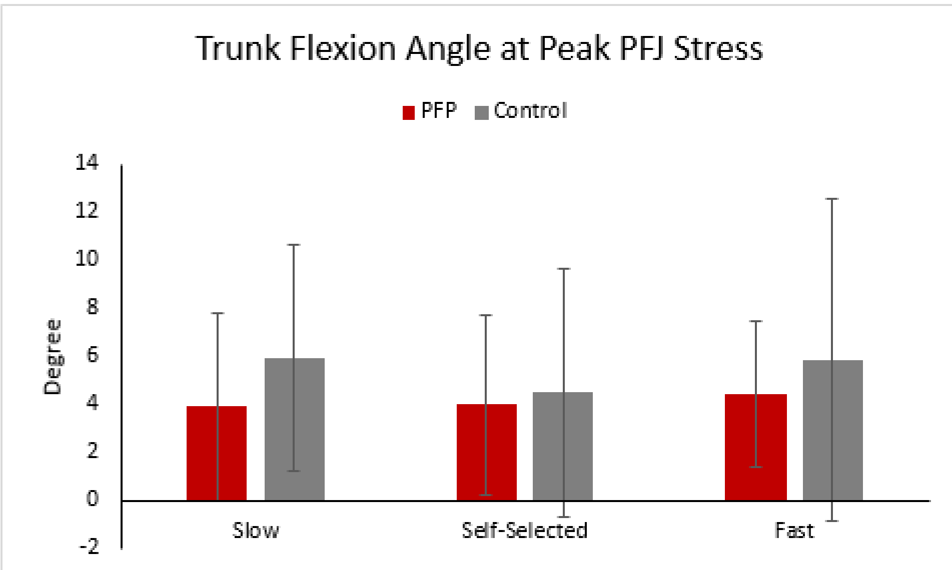
Figure 2. Peak PFJ stress during slow, self-selected, and fast speed running in runners with PFP and pain-free control runners.
PFJ: patellofemoral joint stress
** indicates a significant difference between fast and slow running conditions (P <0.05).*



Trunk Flexion Angle

There was not a group by speed interaction (p=0.540) on trunk flexion angle (Tables 2&3). There was no main effect of group in trunk flexion angle during running (p=0.615). There was also no main effect of running speed on trunk flexion angle (p=0.375) (Figure 3).

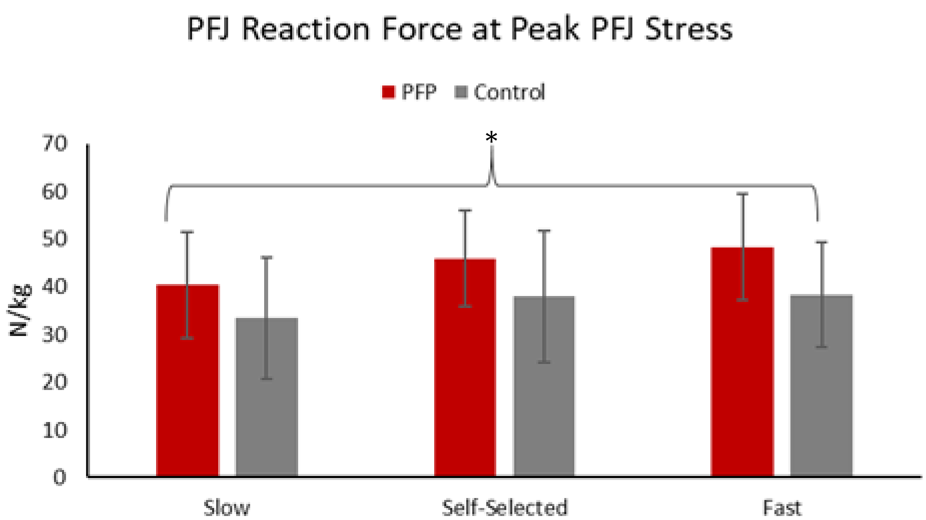
Figure 3. Trunk flexion angle at the time of peak PFJ stress during slow, self-selected, and fast speed running in runners with PFP and pain-free control runners.
PFJ: patellofemoral joint.



Patellofemoral Joint Reaction Force

There was not a group by speed interaction (p=0.707) in PFJ reaction force (Tables 2&3). There was no main effect of group in PFJ reaction force during running (p=0.220). We did observe a significant main effect of speed on PFJ reaction force (p=0.008). In post-hoc testing we observed that PFJ reaction force was significantly lower during slow running than at self-selected (p=0.003) and fast running (p=0.020) speeds across both groups (Figure 4). There was no significant difference in peak PFJ reaction force between fast and self-selected running conditions (p=0.507).

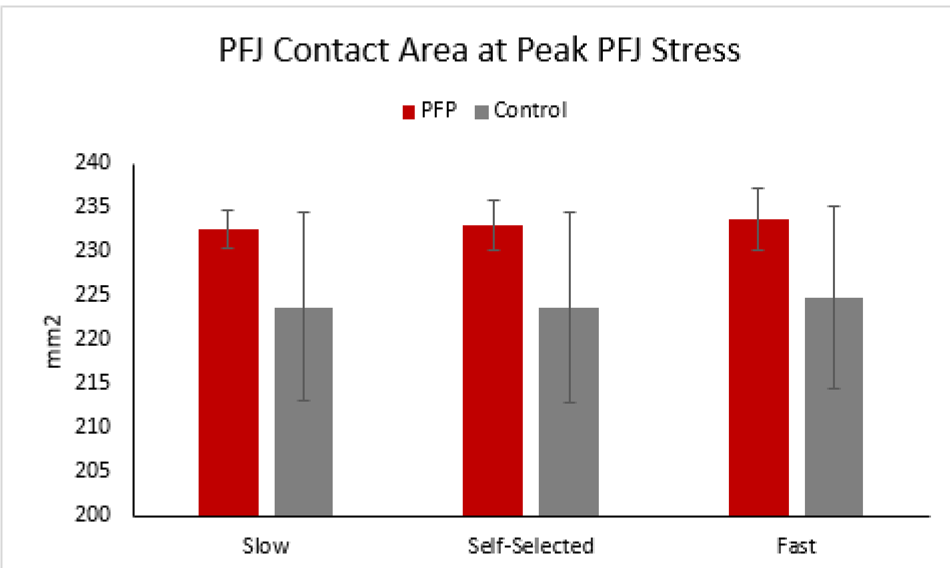
Figure 4. PFJ reaction force at the time of peak PFJ stress during slow, self-selected, and fast speed running in runners with PFP and pain-free control runners.
PFJ: patellofemoral joint.
** indicates a significant difference between fast and slow running conditions (P <0.05).*



Patellofemoral Joint Contact Area

There was not a group by speed interaction ($p=0.925$) in PFJ contact area (Tables 2&3). There was no main effect of group on PFJ contact area during running ($p=0.051$). There was also no main effect of speed on PFJ contact area during running ($p=0.306$). (Figure 5).

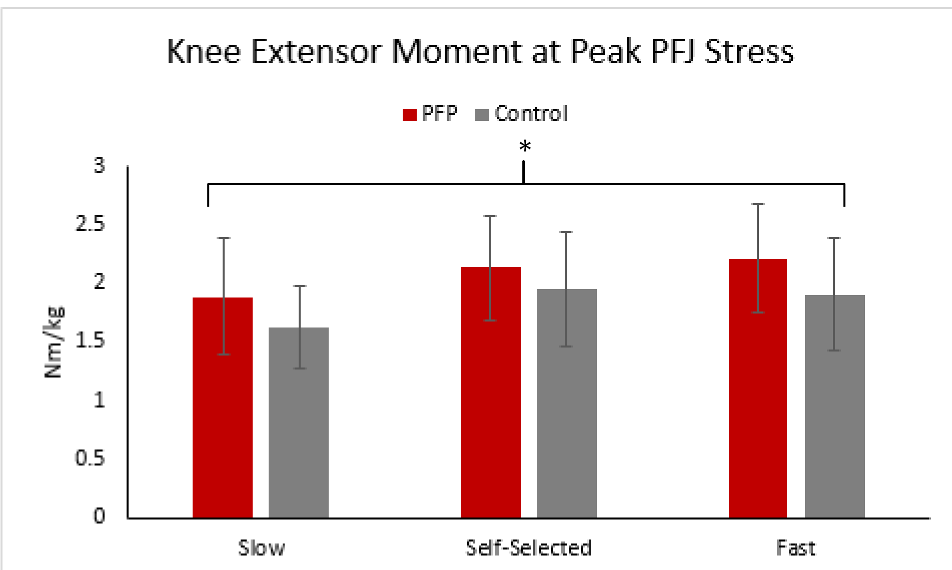
Figure 5. PFJ contact area at the time of peak PFJ stress during slow, self-selected, and fast speed running in runners with PFP and pain-free control runners.
PFJ: patellofemoral joint



Knee Extensor Moment

There was not a group by speed interaction (p=0.635) in knee extensor moment (Tables 2&3). There was no main effect of group on knee extensor moment during running (p=0.349). There was a significant main effect of speed on knee extensor moment (p<0.001). Running at a faster speed caused significantly higher knee extensor moment compared to running at a slow speed (p=0.007). Running at a self-selected speed also had a significantly higher knee extensor moment compared to the slow speed (p<0.001) (Figure 6). There was no significant difference in peak PFJ knee extensor moment between fast and self-selected running conditions (p=0.808).

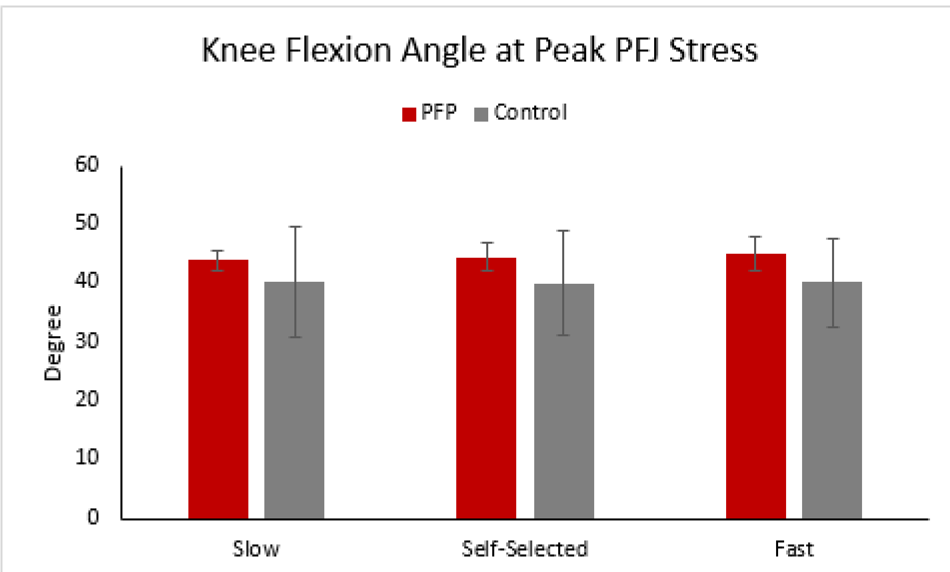
Figure 6. Knee extensor moment at the time of peak PFJ stress during slow, self-selected, and fast speed running in runners with PFP and pain-free control runners.
** indicates a significant difference between fast and slow running conditions (P <0.05). PFJ: patellofemoral joint*



Knee Flexion Angle

There was not a group by speed interaction (p=0.539) in knee flexion angle (Tables 2&3). There was no main effect of group on knee flexion angle during running (p=0.214). There was no main effect of running speed on knee flexion angle (p=0.687) (Figure 7).

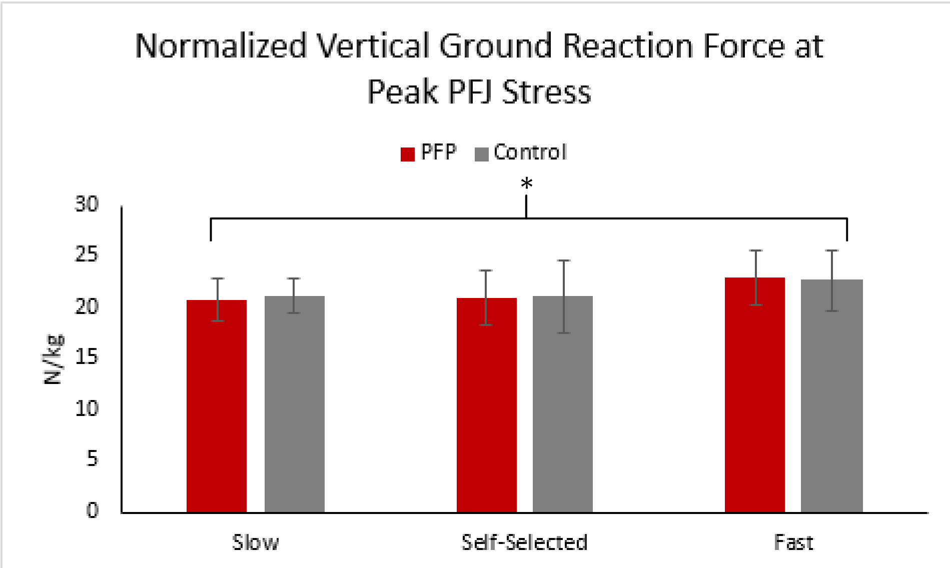
Figure 7. Knee flexion angle at the time of peak PFJ stress during slow, self-selected, and fast speed running in runners with PFP and pain-free control runners.
PFJ: patellofemoral joint



Vertical Ground Reaction Force

There was not a group by speed interaction (p=0.903) in vertical ground reaction force (Tables 2&3). There was no main effect of group on vertical ground reaction force during running (p=0.961). There was a significant main effect of speed on vertical ground reaction force (p=0.007). Vertical ground reaction force was significantly higher during fast running compared to slow running (p=0.012) and self-selected speed (p=0.002) (Figure 8). There was no significant difference between vertical ground reaction force among slow and self-selected speeds (p=0.937).

Figure 8. Vertical ground reaction force at the time of peak PFJ stress during slow, self-selected, and fast speed running in runners with PFP and pain-free control runners.
PFJ: patellofemoral joint
** indicates a significant difference between fast and slow running conditions (P <0.05).*



Discussion

To our knowledge, this is the first study assessing the contribution of trunk flexion angle on PFJ loading when comparing pain-free recreational runners and runners with PFP. The primary purpose of the study was to compare trunk flexion angle and peak PFJ stress of the runners across three different speed conditions (self-selected, fast, and slow speeds). Our findings did not support the hypothesis that runners with PFP would have a decreased trunk flexion angle and increased peak PFJ stress when compared to pain-free runners. We found that there was no significant difference in trunk flexion angle or peak PFJ stress across the three running conditions in runners with PFP compared to pain-free runners.

While the development of PFP pain is complex and multifactorial, increased peak PFJ stress due to a decreased trunk angle and increased knee extensor moment during running are thought to be contributing factors in the development of PFP (Powers 2017). Research by Teng and Powers (2014) showed that healthy runners who were cued to demonstrate an upright trunk posture while running had increased PFJ stress and, conversely, had decreased PFJ stress when cued to demonstrate a more flexed trunk posture. This finding indicates that a more extended trunk posture may be one of the factors contributing to PFJ stress and subsequent PFP pain. However, our study concurred with other research that has failed to find mechanical differences in runners with PFP when compared to pain-free controls (Luz 2018). We, along with Bazett-Jones et al (2013), found similar trunk flexion angles between controls and runners with PFP. We also found similar vertical GRF between controls and runners with PFP, which is supported by Esculier et al (2015).

We found no differences among runners with PFP and controls for any sagittal plane trunk or knee kinematics. It is possible that the 2D PFJ model we used, which incorporated sagittal plane parameters, failed to detect joint stress differences between groups. Luz and dos Santos (2018) detected a difference in frontal and transverse plane motions with greater femoral adduction correlating to greater rearfoot eversion in runners with PFP. Using a 3D finite element model, others have found that excessive femoral adduction and internal rotation in runners with PFP resulted in increased PFJ cartilage stress when compared to pain-free runners (Liao and Powers, 2019).

Other compensatory mechanisms not addressed by our model could explain why we failed to detect kinematic differences among controls and runners with PFP. Bazett-Jones (2013) hypothesized that runners with PFP would have to compensate during an exhaustive run through increased hip flexion angles or anterior pelvic tilt to prevent increases in pain. It is possible there is another compensatory mechanism listed above which increases patellofemoral joint stress which was not measured in our study.

We observed the highest peak PFJ stress during the fast condition in both control and PFP runners, which was mainly driven by a higher GRF, resultant knee extensor moment, and PFJ reaction force. This peak PFJ stress occurred during fast running despite any significant changes in trunk angles; therefore, our study does not support the notion that faster speeds cause an increased trunk flexion angle with consequent reduction in knee extensor moment and PFJ stress. Research by Fisher and Louvw (2018) found greater peak kinematic angles, including increased forward trunk tilt, when they had subjects change from their self-selected speeds to faster or slower speeds. Both slow and fast running increased forward trunk tilt, which further negates the notion that increased speed results in an increased trunk flexion angle. Rather, deviations from self-selected speed in either direction result in similar kinematic changes. Further research examining PFJ stress on runners should occur at self-selected speeds only, as asking participants to change from their self-selected speeds could potentially alter their neuromotor control and cause an increase in peak PFJ stress leading to potentially confounding results.

Our study has several limitations that should be discussed. First, is our sample size. We were unable to complete in-person testing of the 34 participants needed to power our analysis due to the novel coronavirus pandemic. The suspension of testing also prohibited finding a pain-free control match for two subjects with PFP. Additionally, the order of testing conditions was not completely randomized. Runners were told to run at their self-selected speed first, only then was then the order of the fast and slow speeds randomized. Testing was done in a lab with treadmill running and subjects that were traditional outdoor runners stated that it felt unnatural for them. This could have led to altered biomechanics during the running trials as they had to adapt to the lab environment. The joint stress model used in this study is not considered the gold standard of testing, as a cadaveric model is regarded as such; therefore, the absolute PFJ stress values obtained in this study should be interpreted cautiously. It is possible that the coronavirus pandemic contributed to the lack of support for the stated hypothesis in this study by significantly reducing sample size. Further testing is needed to determine if, with the intended sample size, significant differences would be observed across the differing speeds and between the pain-free control group and runners with PFP.

Conclusion

In conclusion, our study suggests that runners with and without PFP exhibited similar peak PFJ stress and trunk flexion angle when running at slow, self-selected, and fast speeds on a treadmill. The clinical relevance of this preliminary work does not support the theory that reduced trunk flexion during running is a contributing factor leading to increased PFJ stress in runners with PFP.

Appendix

Table 2. Summary of variables of interest in runners with PFP (mean±SD). PFP: patellofemoral pain.

	Slow Speed	Self-selected Speed	Fast Speed
Peak patellofemoral joint stress (MPa)	11.8±1.6	13.3±1.6	13.9±1.7
Trunk flexion angle at the time of peak stress (º)	3.9±1.6	4.0±1.6	4.5±1.8
Patellofemoral joint reaction force at the time of peak stress (N/kg)	40.5±4.5	46.0±4.4	48.4±4.2
Patellofemoral joint contact area at the time of peak stress (mm^2)	232.6±2.6	233.1±2.7	233.8±2.7
Knee extensor moment at the time of peak stress (Nm/kg)	1.9±0.2	2.1±0.2	2.2±0.2
Knee flexion angle at the time of peak stress (º)	44.0±2.3	44.5±2.2	45.1±2.0
Ground reaction force at the time of peak stress (N/kg)	20.9±0.7	21.1±1.1	23.0±1.0

Table 3. Summary of variables of interest in pain-free control runners (mean±SD).

	Slow Speed	Self-selected Speed	Fast Speed
Peak patellofemoral joint stress (MPa)	10.9±1.8	12.3±1.8	12.6±2.0
Trunk flexion angle at the time of peak stress (º)	5.9±1.9	4.5±1.9	5.9±2.2
Patellofemoral joint reaction force at the time of peak stress (N/kg)	33.5±5.3	38.0±5.2	38.3±5.0
Patellofemoral joint contact area at the time of peak stress (mm^2)	223.9±3.1	223.8±3.2	224.9±3.2
Knee extensor moment at the time of peak stress (Nm/kg)	1.6±0.2	2.0±0.2	1.9±0.2
Knee flexion angle at the time of peak stress (º)	40.3±2.7	40.0±2.6	40.2±2.3
Ground reaction force at the time of peak stress (N/kg)	21.2±0.9	21.2±1.3	22.8±1.2

Figure 9. Medical History Questionnaire

Age (years): ___________

Sex (M/F):___________

With which leg would you kick a ball? Left ______ Right ______

How many miles do you run per week, on, average?
________miles

What is *currently* your primary sport? (*If more than one, please rank them*)

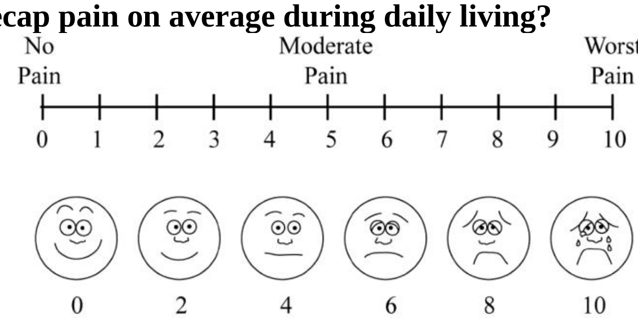
___ Running ___ Triathlon ___ Basketball ___ Volleyball ___ Soccer

What activities do you typically experience kneecap pain?

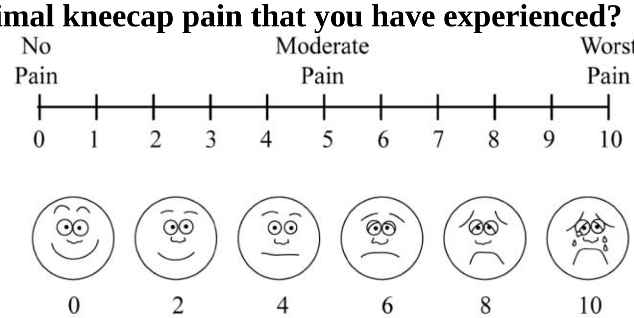
- □ stair climbing
- □ squatting
- □ running
- □ cycling
- □ sitting for prolonged periods with knee bent
- □ others; please specify:______________________________

How long have you had kneecap pain?______________________________

How bad is your kneecap pain on average during daily living?



How bad is your maximal kneecap pain that you have experienced?



Have you ever been diagnosed any knee injuries/diseases? □YES □NO
If yes, please specify: __________________ Date:_____________________
__________________ Date:_____________________

Have you ever have any knee surgery/surgeries? □YES □NO
If yes, please specify: ___________________ Date:______________________
___________________ Date:______________________
___________________ Date:______________________

Do you have history of traumatic patellar dislocation? □YES □NO
If yes, please specify: Date:______________________

Are you currently pregnant or think you may be pregnant? □YES □NO

Figure 10. Subject Screening Tool (filled by investigators)

- Bilateral pain/ unilateral pain
- Side with more symptoms= Right/Left
- Location of pain during palpation:
  □ Peri-patella (medial /lateral/ superior/inferior)
  □ Retro-patella
- Patellar compression test? Positive/Negative
- Weight = _________lb
- Height = ____ft____in

Figure 11. GPAQ Questionnaire

3 GPAQ Question by Question Guide

CORE: Physical Activity

Next I am going to ask you about the time you spend doing different types of physical activity in a typical week. Please answer these questions even if you do not consider yourself to be a physically active person. There are various domains of activity which need to be included; work, activities in and around the home and garden, to get from place-to-place (transport-related) and recreation (discretionary or leisure-time) exercise or sports activities. This opening statement **should not** be omitted.

The respondent will have to think first about the time she/he spends doing work. Work includes things that he/she has to do such as paid or unpaid work, household chores, harvesting food, fishing or hunting for food, seeking employment. [Insert other examples if needed]

In answering the following questions 'vigorous-intensity activities' are activities that require hard physical effort and cause large increases in breathing or heart rate, 'moderate-intensity activities' are activities that require moderate physical effort and cause small increases in breathing or heart rate.

	Questions	Response	Code
	Activity at work		
1	Does your work involve vigorous-intensity activity that causes large increases in breathing or heart rate like *[carrying or lifting heavy loads, digging or construction work]* for at least 10 minutes continuously? *Activities are regarded as vigorous intensity if they cause a large increase in breathing and/or heart rate.* *[INSERT EXAMPLES] (USE SHOWCARD)*	Yes 1 No 2 *If No, go to P 4*	P1
2	In a typical week, on how many days do you do vigorous-intensity activities as part of your work? *"Typical week" means a week when a person is doing vigorous intensity activities and not an average over a period* *Valid responses range from 1-7.*	Number of days └─┘	P2
3	How much time do you spend doing vigorous-intensity activities at work on a typical day? *Think of one day you can recall easily. Consider only those activities undertaken continuously for 10 minutes or more. Probe very high responses (over 4 hrs) to verify*	Hours : minutes └─┴─┘ : └─┴─┘ hrs mins	P3 (a-b)
4	Does your work involve moderate-intensity activity, that causes small increases in breathing or heart rate such as brisk walking *[or carrying light loads]* for at least 10 minutes continuously? *Activities are regarded as moderate intensity if they cause a small increase in breathing and/or heart rate.* *[INSERT EXAMPLES] (USE SHOWCARD)*	Yes 1 No 2 *If No, go to P 7*	P4
5	In a typical week, on how many days do you do moderate-intensity activities as part of your work? *Valid responses range from 1-7*	Number of days └─┘	P5
6	How much time do you spend doing moderate-intensity activities at work on a typical day? *Think of one day you can recall easily. Consider only those activities undertaken continuously for 10 minutes or more. Probe very high responses (over 4 hrs) to verify*	Hours : minutes └─┴─┘ : └─┴─┘ hrs mins	P6 (a-b)
	Travel to and from places		
	The next questions exclude the physical activities at work that you have already mentioned. Now I would like to ask you about the usual way you travel to and from places. For example to work, for shopping, to market, to place of worship. [insert other examples if needed] *The introductory statement to the following questions on transport-related physical activity is very important. It asks and helps the participant to now think about how they travel around getting from place-to-place. This statement **should not** be omitted.*		
7	Do you walk or use a bicycle (*pedal cycle*) for at least 10 minutes continuously to get to and from places? *Circle the appropriate response*	Yes 1 No 2 *If No, go to P 10*	P7
8	In a typical week, on how many days do you walk or bicycle for at least 10 minutes continuously to get to and from places? *Valid responses range from 1-7*	Number of days └─┘	P8

Continued on next page

9	How much time do you spend walking or bicycling for travel on a typical day? *Think of one day you can recall easily. Consider the total amount of time walking or bicycling for trips of 10 minutes or more. Probe very high responses (over 4 hrs) to verify.*	Hours : minutes └─┴─┘ : └─┴─┘ hrs mins	P9 (a-b)
Recreational activities			
The next questions exclude the work and transport activities that you have already mentioned. Now I would like to ask you about sports, fitness and recreational activities (leisure),[insert relevant terms]. *This introductory statement directs the participant to think about recreational activities. This can also be called discretionary or leisure time. It includes sports and exercise but is not limited to participation competitions. Activities reported should be done regularly and not just occasionally. It is important to focus on only recreational activities and not to include any activities already mentioned. This statement **should not** be omitted.*			
10	Do you do any vigorous-intensity sports, fitness or recreational (*leisure*) activities that cause large increases in breathing or heart rate like [*running or football,*] for at least 10 minutes continuously? *[INSERT EXAMPLES] (USE SHOWCARD)* ? *Activities are regarded as vigorous intensity if they cause a large increase in breathing and/or heart rate.*	Yes 1 No 2 *If No, go to P 13*	P10
11	In a typical week, on how many days do you do vigorous-intensity sports, fitness or recreational (*leisure*) activities? *Valid responses range from 1-7*	Number of days └─┘	P11
12	How much time do you spend doing vigorous-intensity sports, fitness or recreational activities on a typical day? *Think of one day you can recall easily. Consider the total amount of time doing vigorous recreational activities for periods of 10 minutes or more. Probe very high responses (over 4 hrs).*	Hours : minutes └─┴─┘ : └─┴─┘ hrs mins	P12 (a-b)
13	Do you do any moderate-intensity sports, fitness or recreational *(leisure*) activities that causes a small increase in breathing or heart rate such as brisk walking,(*cycling, swimming, volleyball*)for at least 10 minutes continuously? *Activities are regarded as moderate intensity if they cause a small increase in breathing and/or heart rate.* *[INSERT EXAMPLES] (USE SHOWCARD)*	Yes 1 No 2 *If No, go to P16*	P13
14	In a typical week, on how many days do you do moderate-intensity sports, fitness or recreational (*leisure*) activities? *Valid responses range from 1-7*	Number of days └─┘	P14
15	How much time do you spend doing moderate-intensity sports, fitness or recreational (*leisure*) activities on a typical day? *Think of one day you can recall easily. Consider the total amount of time doing moderate recreational activities for periods of 10 minutes or more. Probe very high responses (over 4 hrs).*	Hours : minutes └─┴─┘ : └─┴─┘ hrs mins	P15 (a-b)
Sedentary behaviour			
The following question is about sitting or reclining at work, at home, getting to and from places, or with friends including time spent [sitting at a desk, sitting with friends, travelling in car, bus, train, reading, playing cards or watching television], but do not include time spent sleeping. *[INSERT EXAMPLES] (USE SHOWCARD)*			
16	How much time do you usually spend sitting or reclining on a typical day? *Consider total time spent at work sitting, in an office, reading, watching television, using a computer, doing hand craft like knitting, resting etc. Do not include time spent sleeping.*	Hours : minutes └─┴─┘ : └─┴─┘ hrs min s	P16 (a-b)

References

Bazett-Jones, D. M., Cobb, S. C., Huddleston, W. E., O'CONNOR, K. M., Armstrong, B. S., & Earl-Boehm, J. E. (2013). Effect of patellofemoral pain on strength and mechanics after an exhaustive run. Medicine & Science in Sports & Exercise, 45(7), 1331-1339.

Chumanov, E. S., Wille, C. M., Michalski, M. P., & Heiderscheit, B. C. (2012). Changes in muscle activation patterns when running step rate is increased. *Gait & Posture, 36*(2), 231-235. doi:10.1016/j.gaitpost.2012.02.023

Collins, T. D., Ghoussayni, S. N., Ewins, D. J., & Kent, J. A. (2009). A six degrees-of-freedom marker set for gait analysis: repeatability and comparison with a modified Helen Hayes set. *Gait & Posture, 30*(2), 173-180. doi:10.1016/j.gaitpost.2009.04.004

Esculier, J. F., Roy, J. S., & Bouyer, L. J. (2015). Lower limb control and strength in runners with and without patellofemoral pain syndrome. Gait & posture, 41(3), 813-819.

Fisher, D., Louw, Q., Cockcroft, J., & Tawa, N. (2018). Three-dimensional kinematics of the thorax during over-ground running. *J Bodyw Mov Ther, 22*(2), 300-307. doi:10.1016/j.jbmt.2017.08.003

Francis, P., Whatman, C., Sheerin, K., Hume, P., & Johnson, M. I. (2019). The Proportion of Lower Limb Running Injuries by Gender, Anatomical Location and Specific Pathology: A Systematic Review. *Journal of Sports Science and Medicine, 18*(1), 21-31.

Hahn, H., Vincent, K. R., Herman, D. C., Chen, C., Zdziarski, L. A., Morgan, C., & Vincent, H. K. (2017). Biomechanical, metabolic and cardiopulmonary responses of masters recreational runners during running at different speeds. *Research in Sports Medicine, 25*(2), 118-131. doi:10.1080/15438627.2017.1282359

Ho, K. Y., French, T., Klein, B., & Lee, Y. (2018). Patellofemoral joint stress during incline and decline running. *Physical Therapy in Sport, 34*, 136-140. doi:10.1016/j.ptsp.2018.09.010

Ho, K. Y., Hu, H. H., Colletti, P. M., & Powers, C. M. (2014). Recreational runners with patellofemoral pain exhibit elevated patella water content. *Magn Reson Imaging, 32*(7), 965-968. doi:10.1016/j.mri.2014.04.018

Lenhart, R. L., Thelen, D. G., Wille, C. M., Chumanov, E. S., & Heiderscheit, B. C. (2014). Increasing Running Step Rate Reduces Patellofemoral Joint Forces. *Medicine and Science in Sports and Exercise, 46*(3), 557-564. doi:10.1249/MSS.0b013e3182a78c3a

Liao, T., & Powers, C. M. (2019). Tibiofemoral kinematics in the transverse and frontal planes influence the location and magnitude of peak patella cartilage stress: An investigation of runners with and without patellofemoral pain. *Clinical Biomechanics, 62*, 72-78. doi:10.1016/j.clinbiomech.2019.01.00

Luz, B. C., Santos, A. F., Souza, M. C., Sato, T. D., Nawoczenski, D. A., & Serrão, F. V. (2018). Relationship between rearfoot, tibia and femur kinematics in runners with and without patellofemoral pain. Gait & Posture, 61, 416-422. doi:10.1016/j.gaitpost.2018.02.008

Powers, C. M., Witvrouw, E., Davis, I. S., & Crossley, K. M. (2017). Evidence-based framework for a pathomechanical model of patellofemoral pain: 2017 patellofemoral pain consensus statement from the 4th International Patellofemoral Pain Research Retreat, Manchester, UK: part 3. *British Journal of Sports Medicine, 51*(24), 1713-1723. doi:10.1136/bjsports-2017-098717

Santos, A. F., Nakagawa, T. H., Lessi, G. C., Luz, B. C., Matsuo, H. T., Nakashima, G. Y., . . . Serrão, F. V. (2019). Effects of three gait retraining techniques in runners with patellofemoral pain. *Physical Therapy in Sport, 36*, 92-100. doi:10.1016/j.ptsp.2019.01.006

Smith, J. A., & Kulig, K. (2016). Trunk-pelvis coordination during turning: A cross sectional study of young adults with and without a history of low back pain. *Clin Biomech (Bristol, Avon), 36*, 58-64. doi:10.1016/j.clinbiomech.2016.05.011

Teng, H. L., & Powers, C. M. (2014). Sagittal Plane Trunk Posture Influences Patellofemoral Joint Stress During Running. *Journal of Orthopaedic & Sports Physical Therapy, 44*(10), 785-792. doi:10.2519/jospt.2014.5249

van Eijden, T. M., Weijs, W. A., Kouwenhoven, E., & Verburg, J. (1987). Forces acting on the patella during maximal voluntary contraction of the quadriceps femoris muscle at different knee flexion/extension angles. *Acta Anat (Basel), 129*(4), 310-314.

Walter, S. D., Hart, L. E., Mcintosh, J. M., & Sutton, J. R. (1989). The Ontario Cohort Study of Running-Related Injuries. *Archives of Internal Medicine, 149*(11), 2561-2564. doi:DOI 10.1001/archinte.149.11.2561

Zuk, M., & Pezowicz, C. (2015). Kinematic Analysis of a Six-Degrees-of-Freedom Model Based on ISB Recommendation: A Repeatability Analysis and Comparison with Conventional Gait Model. *Appl Bionics Biomech, 2015*, 503713. doi:10.1155/2015/503713

Curriculum Vitae

Zachary A. Clark, SPT

Department of Physical Therapy
University of Nevada, Las Vegas
Las Vegas, NV 89154
Department Phone: (702) 895-3003
Email: zacclark12@gmail.com

Education

University of Nevada, Las Vegas
D.P.T., May 2021

University of Hawai'i at Mānoa
B.S., December 2017

Christine DuVall, SPT

Department of Physical Therapy
University of Nevada, Las Vegas
Las Vegas, NV 89154
Department Phone: (702) 895-3003
Email: Christineduvall96@gmail.com

Education

University of Nevada, Las Vegas
D.P.T., May 2021

Rocky Mountain College
B.S., May 2018

Tavin Fox, SPT

Department of Physical Therapy
University of Nevada, Las Vegas
Las Vegas, NV 89154
Department Phone: (702) 895-3003
Email: tavin.fox@gmail.com

Education

University of Nevada, Las Vegas
D.P.T., May 2021

University of Nevada, Las Vegas
B.S., December 2017

Caitlin Howden, SPT

Department of Physical Therapy
University of Nevada, Las Vegas
Las Vegas, NV 89154
Department Phone: (702) 895-3003
Email: cdevittpayne@gmail.com

Education

University of Nevada, Las Vegas
D.P.T., May 2021

University of Nevada, Reno
B.S., May 2016