The effects & mechanisms of increasing running step rate: a feasibility study in a mixed-sex group of runners with patellofemoral pain

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Abstract

Objectives: To explore feasibility of recruitment and retention of runners with patellofemoral pain (PFP), before delivering a step rate intervention.

Design: Feasibility study

Setting: Human performance laboratory

Participants: A mixed-sex sample of runners with PFP (n=11).

Main Outcome Measures: Average/worst pain and the Kujala Scale were recorded pre/post intervention, alongside lower limb kinematics and surface electromyography (sEMG), sampled during a 3KM treadmill run.

Results: Recruitment and retention of a mixed-sex cohort was successful, losing one participant to public healthcare and with kinematic and sEMG data lost from single participants only. Clinically meaningful reductions in average (MD=2.1, *d*=1.7) and worst pain (MD=3.9, *d*=2.0) were observed. Reductions in both peak knee flexion (MD=3.7˚, *d*=0.78) and peak hip internal rotation (MD=5.1˚, *d*=0.96) were observed, which may provide some mechanistic explanation for the identified effects. An increase in both mean amplitude (*d*=0.53) and integral (*d*=0.58) were observed for the Vastus Medialis Obliqus (VMO) muscle only, of questionable clinical relevance.

Conclusions: Recruitment and retention of a mixed sex PFP cohort to a step rate intervention involving detailed biomechanical measures is feasible. There are indications of both likely efficacy and associated mechanisms. Future studies comparing the efficacy of different running retraining approaches are warranted.

Key Words

Patellofemoral Pain, Running, Biomechanics, Electromyography

INTRODUCTION

Recreational running positively influences cardiac, (Petrovic-Oggiano, Damjanov, Gurinovic, & Glibetic, 2010) metabolic (Williams, 2014) and mental (Ghorbani, et al., 2014) health. Despite the reported benefits, recreational running is reported to bring about an increased risk of musculoskeletal pain. (Saragiotto, et al., 2014; van Gent, et al., 2007) Overall incidence of musculoskeletal pain amongst recreational runners ranges from 19% to 94%, (van Gent, et al., 2007) with patellofemoral pain (PFP) thought to be the most common. (Taunton, et al., 2002) Specific annual incidence of PFP amongst recreational runners ranges from 4% to 21%, (Noehren, Hamill, & Davis, 2013; Ramskov, Barton, Nielsen, & Rasmussen, 2015; Thijs, Van Tiggelen, Roosen, De Clercq, & Witvrouw, 2007), with overall prevalence in sports medicine facilities suggested to be 17%. (Taunton, et al., 2002)

Running biomechanics has been reported to be a risk factor for, and associated with, running related PFP. Specifically, peak hip adduction during running has been reported to be significantly higher in female runners who develop subsequent PFP when compared to those who remain asymptomatic. (Neal, Barton, Gallie, O'Halloran, & Morrissey, 2016; Noehren, et al., 2013) In addition, based on our recent meta-analysis, (Neal, et al., 2016) peak hip adduction, peak hip internal rotation and contralateral pelvic drop are also significantly higher in runners with PFP when compared to asymptomatic controls. For neuromuscular function, females with PFP have been reported to have a delayed gluteal onset prior to foot contact and shorter gluteal activation duration compared to asymptomatic controls. (Willson, Kernozek, Arndt, Reznichek, & Scott Straker, 2011)

At present, evidence suggests that exercise interventions, whilst effective at reducing symptoms in runners with PFP in the short-term, do not result in full symptom resolution. (Earl & Hoch, 2011; Ferber, Kendall, & Farr, 2011) Moreover, exercise may not derive its effects by way of a kinematic mechanism, as multiple studies have demonstrated that exercise programs designed to increase hip strength do not alter running kinematics thought to be associated with PFP. (Earl & Hoch, 2011; Sheerin, Hume, & Whatman, 2012; Willy & Davis, 2011; Wouters, et al., 2012) This brings into question the ability of an exercise intervention to provide long-term resolution to running related PFP, as it fails to target factors known to be associated with the development and persistence of the condition. It is this premise that originally led to the development of what has been termed running retraining, (Heiderscheit, 2011) or more specifically 'the implementation of any cue or strategy designed to alter an individual's running technique'. (I. Davis, 2005)

Reports from observational studies, involving visual and verbal cues to reduce peak hip adduction, indicates running retraining may reduce pain and improve function in female runners with PFP who demonstrate more than 20˚ peak hip adduction during running. (Neal, et al., 2016; Noehren, Scholz, & Davis, 2011; Willy, Scholz, & Davis, 2012) The key limitation of this work is that the results can only be extrapolated to a minority of runners with PFP (i.e. females with high peak hip adduction). In addition, a recently completed randomised controlled trial (RCT) has established efficacy for cues to transition from rearfoot to forefoot strike in combination with a load management running program in a mixed-sex, but again a predominantly female, cohort. (Roper, et al., 2016) The limitation of this study is that cues to transition to a forefoot strike are only applicable to those who rearfoot strike at baseline. Additionally, it is thought that such a change to running mechanics may also be injurious by virtue of the increase in Achilles tendon load that is observed with forefoot strike running compared to rearfoot strike running. (Rice & Patel, 2017) This is reinforced by the fact that 25% (2/8) of the runners in this RCT who transitioned to a forefoot strike pattern reported ankle soreness at follow up. (Roper, et al., 2016)

It has been reported that cues to increase running step rate do not increase Achilles tendon load (Lyght, Nockerts, Kernozek, & Ragan, 2016) and thus may be a more widely applicable running retraining option to those previously studied. A recent feasibility study has reported that a step rate increase of 10% combined with running in a minimalist shoe was superior to foot orthoses at reducing pain and improving function at 12 week follow up in runners with PFP. (Bonacci, Hall, Saunders, & Vicenzino, 2017) An increase in step rate of 10% has also been reported to favourably alter patellofemoral joint stress in both runners with PFP and asymptomatic runners, (Willson, Sharpee, Meardon, & Kernozek, 2014), though the actual reduction in step length reported was much greater (14%). In addition, no evaluation of symptoms could be reported in this study due to the limitation of the cross-sectional, observational design. Observational work in asymptomatic runners also indicates that more modest increases in running step rate of 5% or 7.5% may still reduce peak hip adduction (Heiderscheit, Chumanov, Michalski, Wille, & Ryan, 2011; Willy, et al., 2015), albeit of a smaller magnitudes.

A recent three-arm RCT (Esculier, et al., 2017) found that a running retraining intervention to increase step rate was no more effective than education focused on load management, or compared to the same education combined with exercise therapy in runners with PFP. Whilst no treatment group had superior outcomes, the step rate intervention did result in significant reductions in both worst and running specific pain. All three groups remained symptomatic at the primary end point (20 weeks), and running-related pain was higher (2.5/10) in the step rate group compared to previous studies where hip adduction (0.5/10) (Noehren, et al., 2011; Willy, et al., 2012) and strike pattern (1.0/10) (Roper, et al., 2016) has been targeted. This could be explained by the absence of a faded-feedback protocol to facilitate the retraining intervention, (Irene Davis, 2017) which has been found to be effective by previous studies. (Noehren, et al., 2011; Roper, et al., 2016; Willy, et al., 2012)

The primary aim of this study was to investigate the feasibility of a pragmatic running retraining intervention, by cueing a 7.5% increase in running step rate using a faded feedback protocol. Specific objectives included (i) the recruitment of an appropriate number of both males and females from a clinical population and (ii) the collection of both symptom and function data to determine an estimate of the effects derived from the intervention. The secondary aim was to investigate the potential kinematic and muscle function mechanisms explaining any effects induced by the intervention.

METHODS

Participants

Ethical approval for this study was granted by the Queen Mary Ethics of Research Committee (QMREC2014/63). All participants provided written informed consent prior to study commencement. Participants were recruited from local sports medicine clinics. Sample size was based on the apriori power analysis conducted by the authors of the previous work on running retraining, (Noehren, et al., 2011; Willy, et al., 2012) leading to a total of 10 participants being sought. Participants were of either sex, currently or previously running a minimum of 10 km/week and aged between 18 and 45 years. To be included, participants were required to have atraumatic retropatellar or peripatellar pain during running and one other activity described by the most recent PFP consensus document, which includes squatting, stair ambulation and jumping. (Crossley, et al., 2016) Patellofemoral symptoms needed to be rated at a minimum of three (out of a maximum of 10) using a numerical rating scale (NRS). Potential participants with patellofemoral instability, previous surgery, tibiofemoral pathology or any pathology (musculoskeletal or otherwise) that precluded running participation were excluded.

Experimental Protocol

Included participants were required to present to the Human Performance Laboratory at Queen Mary University of London. In the presence of bilateral symptoms, the knee that scored highest on the numerical rating scale was analysed. In the presence of equivocal symptoms, the dominant limb that would be used to kick a ball was analysed. (Willy, et al., 2012) Both limbs were not entered into the analysis in the presence of bilateral symptoms given the potential for type I error. (Menz, 2005) Prior to data collection, participants completed the Kujala Scale as a subjective measure of function. (Kujala, et al., 1993) The Kujala Scale is a 13-question appraisal of subjective function in those with PFP, with a score of 100 representing no symptoms and a score of 0 indicating complete disability. Participants were also required to rate their average and worst pain in the past week from 0 to 10 using an NRS. Whilst there is no definitive outcome measure for use with a PFP cohort, the NRS and Kujala Scale are reported to be the most valid and responsive measures for detecting change at time of study commencement. (Crossley, Bennell, Cowan, & Green, 2004)

Kinematic Measures

Participant movement data were collected during running using a four-camera, infrared motion analysis system (CX-1, Codamotion, Charnwood Dynamics Limited, Leicestershire, UK). (Lack, et al., 2014) 24 infrared markers, consisting of eight individual markers and four rigid clusters of four markers, were placed on standard pelvic and lower limb anatomical landmarks using the CAST protocol. (Cappello, Cappozzo, La Palombara, Lucchetti, & Leardini, 1997) Markers from the pelvis frame to the knee joint centre tracked the thigh segment and markers from the knee joint centre to the ankle joint centre tracked the shank segment. Individual markers were applied using double-sided adhesive tape and secured with transparent surgical tape, with the rigid clusters applied using adjustable elastic straps and secured with cohesive self-adherent bandage. Virtual markers were also identified on the femoral epicondyles and the ankle malleoli, to allow for the calculation of relevant joint centers during an upright standing trial. The hip joint centre was estimated as a projection within the pelvis frame using the methods described by Bell et al (Bell, Pedersen, & Brand, 1990) and did not vary between male and female subjects. The knee joint centre was estimated as the mid-point between the femoral epicondyle markers.

Participants were asked to run in their usual running shoes and self-select their typical 'steady state' running speed on the laboratory treadmill (Kistler Gaitway, Kistler Group, Winterthur, Switzerland). Participants were instructed to run for a total of three kilometers (KM), with the option to cease if symptoms increased to four or greater on the NRS. 10 seconds of data sampled at 200Hz were collected at 0.8/1.8/2.8KM, with distance as opposed to time chosen to act as a constant measure across a cohort of participants running at differing speeds. Multiple data collections were completed to increase reliability of gait analysis. (Monaghan, Delahunt, & Caulfield, 2007) Based on between group differences identified in our recent meta-analysis, (Neal, et al., 2016) variables of interest included peak hip adduction, internal rotation and flexion, peak knee flexion and contralateral pelvic drop, given their retrospective association with PFP.

Electromyography Measures

Surface muscle electromyography (sEMG) were collected simultaneously with the kinematic data using a wireless Delsys TRIGNO system (DELSYS Inc., Natick, Massachusetts, USA). Prior to application, participant's skin was marked, shaved and cleaned with an alcohol swab. Self-contained bipolar electrodes were placed at the motor points of the Gluteus Maximus (GMAX), Gluteus Medius (GMED), Semitendinosus (ST) and Vastus Medialis Obliqus (VMO) adhering to SENIAM guidelines. (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000) 10 seconds of sEMG data sampled at 1926Hz were collected at three specific distance points as described above, but were not synchronised to the kinematic data.

Running Retraining Intervention

Participants completed 18 retraining sessions over the course of six weeks. Each week involved a total of three individual runs, equating to 18 runs in total. For the first four weeks, the initial run was completed in a supervised fashion with the primary investigator (BSN). During the retraining sessions, participants were cued via an audio metronome set at 7.5% above their baseline step rate (calculated during data acquisition), based on the previous work of Willy et al (Willy, et al., 2015). The additional two runs each week were completed independently. A faded feedback protocol successfully used previously was adopted. (Noehren, et al., 2011; Willy, et al., 2012) Feedback exposure was gradually reduced and treadmill run time was gradually increased from 10 minutes to 30 minutes (see figure 1), to facilitate skill acquisition. A slower progression from 10-30 minutes was used (18 sessions over six weeks) compared to previous work (8-10 sessions over two to four weeks), to better adhere to contemporary training progression approaches. (Gabbett, 2016) Further, this pace of progression is used clinically in the chosen recruitment centre, minimising ethical issues from varying usual care. For the final two weeks, all completed sessions were performed independently, without any metronome feedback. All data were collected prior to, and after completion of, the running retraining intervention.

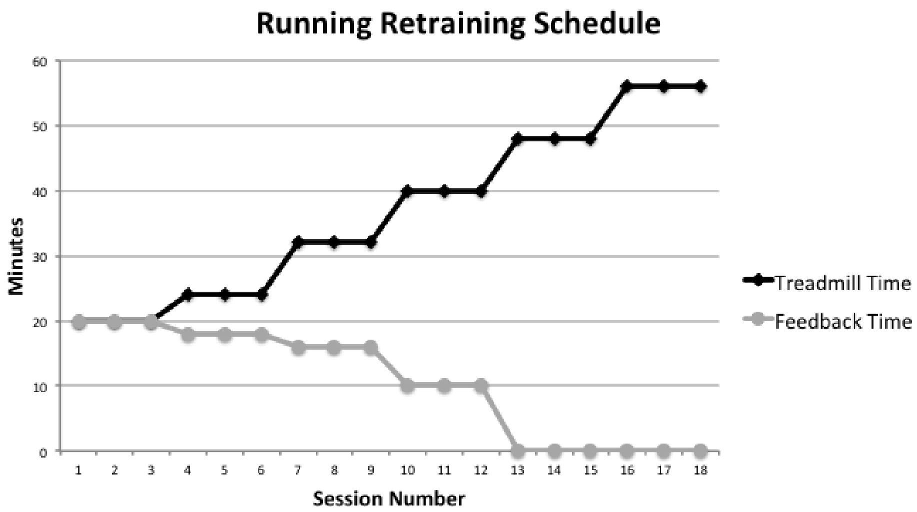

Figure 1: running retraining schedule depicting the faded feedback protocol employed.

Kinematic Data Analysis

Data were analysed offline using a custom written Matlab program (version 2015, Mathworks, Natick, Massachussets, USA). Initial foot contact and toe off were identified using the heel marker on the calcaneal tuberosity and the metatarsal marker on the fifth metatarsal head in the vertical (Z) plane. Consistent with previously described methods, initial foot contact was defined as the point at which the heel marker ceased its descent in the vertical plane. (Zeni, Richards, & Higginson, 2008) Toe off was identified using a combination of the heel and metatarsal markers. Specifically, peak acceleration of the metatarsal marker was identified within a specific time point defined by the 70% or greater of the absolute maximum velocity region of the heel marker. (Zeni, et al., 2008) All kinematic data were aligned to initial foot contact, interpolated and normalised to percentage of stride cycle (0% =

initial contact, 100% = terminal stance) to facilitate data analysis. Clinical relevance of kinematic data was interpreted with reference to the minimum detectable change data reported by Noehren et al. (Noehren, Manal, & Davis, 2010)

sEMG Data Analysis

sEMG data were processed using an in-built band-pass filter from 25-500 Hz. Raw sEMG data were decomposed using wavelets. (Reaz, Hussain, & Mohd-Yasin, 2006) Post-wavelet decomposition, data were cut into strides using the mean total wavelet power of the VMO muscle, as the typical activation pattern of this muscle (onset/offset) during running is known to align closely to the initial contact (onset) and toe off (offset) phases of running gait. (Flynn & Soutas-Little, 1993) These stride cycle timings were then applied to all sEMG data. Pre and post retraining data were cut into strides independently, but were not used to describe sEMG data as though it were synchronised to the true kinematic gait cycle of the participant. As participants are unlikely to reach signal intensity akin to maximal voluntary isometric contraction (MVIC) during steady state running, data were normalised to the mean of the peak dynamic signal intensity across a single set of strides (0.8KM trial, pre-retraining), which has been reported to be more valid than normalizing to maximal dynamic signal peak. (Bolgla & Uhl, 2007)

Statistical Analysis

All statistical testing were performed offline using Microsoft Excel (Microsoft Corporation, Albuquerque, New Mexico, USA). A Cohen's *d* was calculated to determine the size of all identified interactions, alongside the reporting of mean differences and 95% confidence intervals (CI). Cohen's *d* was interpreted as small (≤ 0.2), medium (>0.5) and large (>0.8) respectively. (Sullivan & Feinn, 2012) As a feasibility study, not powered apriori to detect statistical significance, dependent sample *t-tests* were not performed and p-values for differences not reported because of the potential for type II error and to avoid giving the impression of there being robust findings from a feasibility study design. The main outcomes were those of recruitment, retention and measurement feasibility.

RESULTS

A total of 10 (out of 11) participants (four male, six female) completed the study. One female participant was lost to follow up due to a switch of care provision to the National Health Service. Demographics and baseline characteristics of the participants who completed the study are described in table 1.

Table 1

Variable	**Mean (SD)**
Sex (Male/Female)	4/6
Age (Years)	31.6 (5.5)
Height (cm)	170.6 (7.8)
Mass (kg)	67.7 (9.8)
Symptom duration (Months)	45.1 (32.1)
Average run volume (KM)	17.0 (9.8)
Step rate (SPM)	163.6 (4.7)
Kujala scale	86.4/100 (6.9)
Average NRS	3.0/10 (1.6)
Worst NRS	6.8/10 (1.5)

Participant characteristics

Key: cm=centimeters; kg=kilograms; KM=kilometers; SPM=steps per minute; NRS=numerical rating scale.

Effects

Large reductions in both average (*d*=1.7) and worst (*d*=2.0) pain were identified post-retraining. The mean difference (MD) of these reductions was 2.1 and 3.9 NRS points respectively and individual participant worst pain responses to the retraining intervention ranged from 1 to 8 NRS points (see figure 2). A modest improvement in function measured with the Kujala Scale was also identified (*d*=0.12), with a mean difference of 4.4 points.

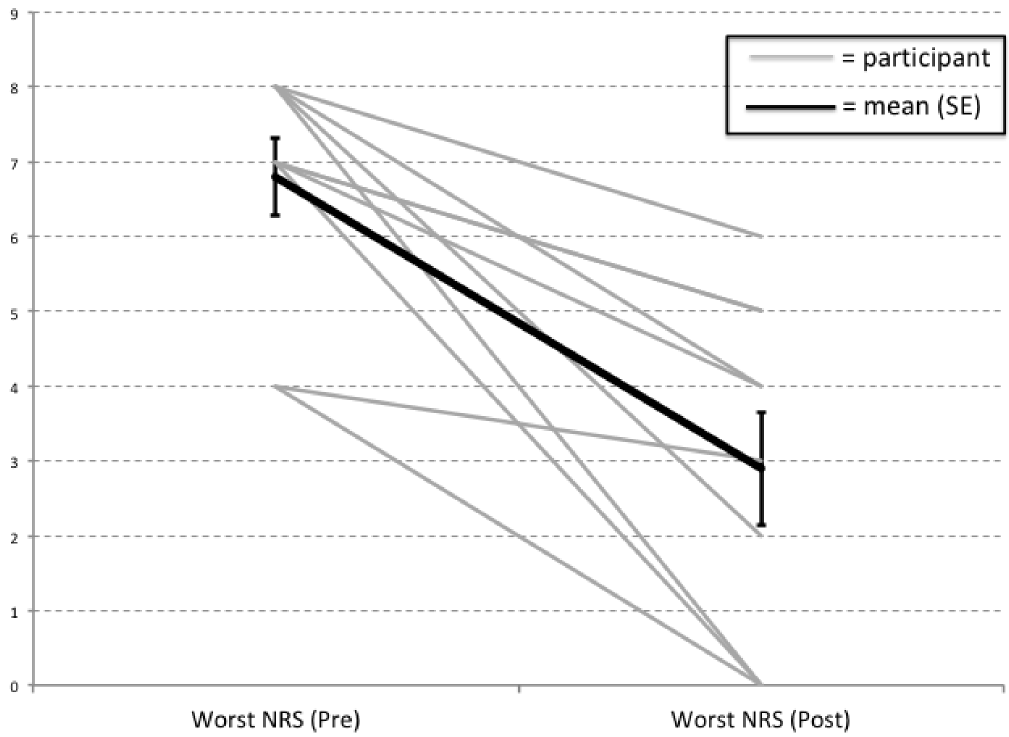

Figure 2: mean pooled and individual worst pain responses at baseline (pre) and six weeks follow up (post).

Mechanisms

Spatiotemporal

An increase in running step rate at six weeks follow up was observed, with a mean increase of 7.8% (range 2.3% - 11.1%). 3 participants did not achieve a step rate of ≥ 7.5% post retraining.

Kinematics

One participant was found to have consistently corrupted marker data throughout their trials and was therefore removed from the kinematic analysis. This resulted in a kinematic sample of nine participants (five females, four males). Moderate reductions in both peak knee flexion (MD=3.7˚, *d*=0.78) (see figure 4a) and peak hip adduction (MD=2.4˚, *d*=0.54) (see figure 4b) were identified post-retraining. A large reduction in peak hip internal rotation was also identified post retraining (MD=5.1˚, *d*=0.96) (see figure 4c). A full breakdown of the kinematic analysis can be seen in table 2 and individual participant spatiotemporal and kinematic responses in relation to average/worst pain at six-week follow up are presented in table 3.

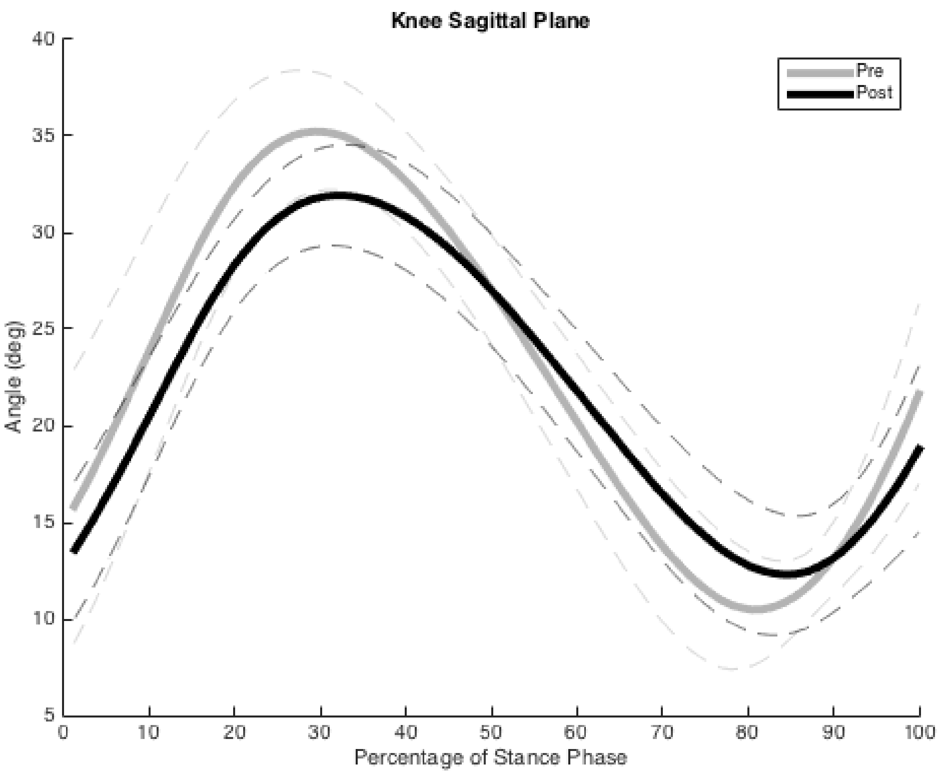

Figure 4a: mean pattern of hip knee flexion throughout stance at baseline (pre) and six week follow up (post). Knee flexion is positive. Solid line = mean. Dashed line = 95% confidence intervals.

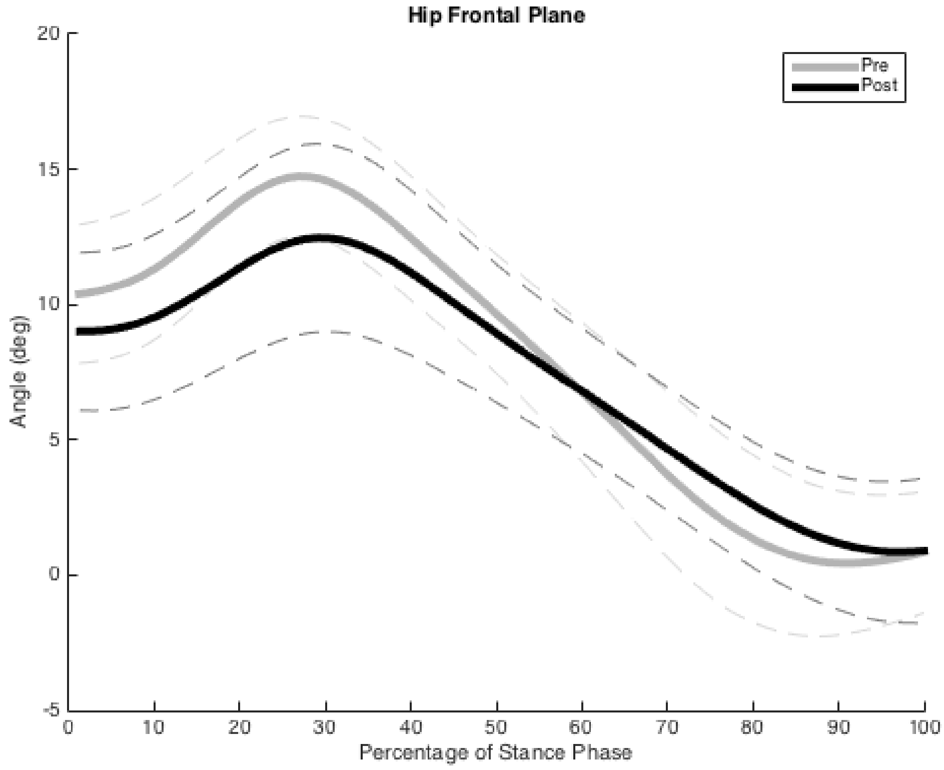

Figure 4b: mean pattern of hip adduction throughout stance at baseline (pre) and six week follow up (post). Hip adduction is positive. Solid line = mean. Dashed line = 95% confidence intervals.

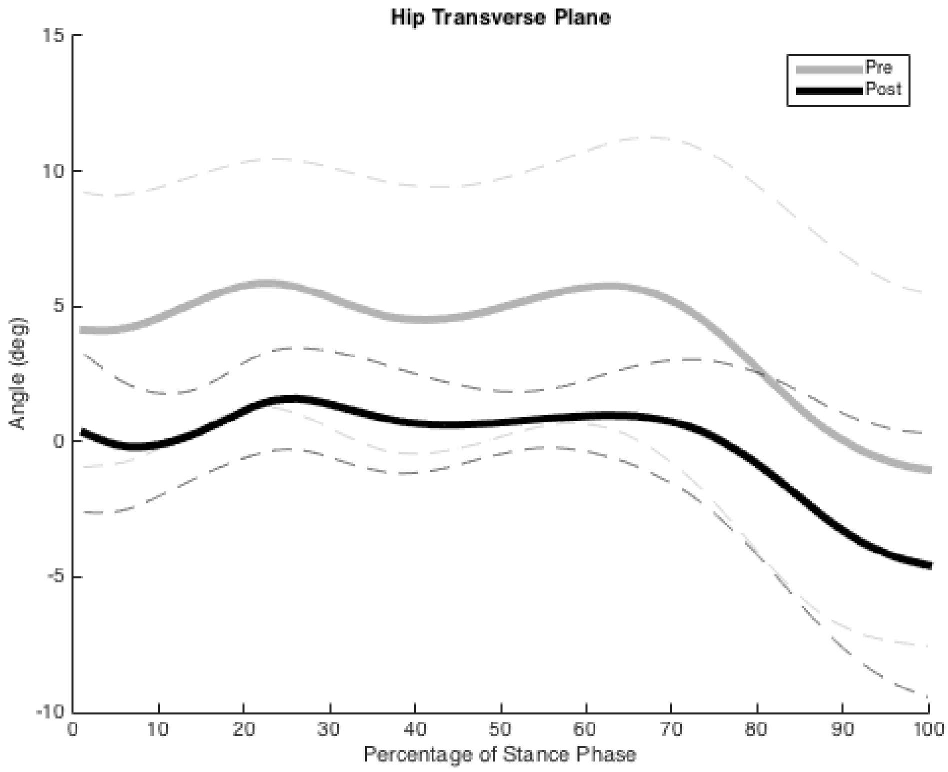

Figure 4c: mean pattern of hip internal rotation throughout stance at baseline (pre) and six week follow up (post). Hip internal rotation is positive. Solid line = mean. Dashed line = 95% confidence intervals.

Table 2

Variable	Pre	Post	Mean Difference	95% CI	Cohen's *d*
	Mean (SD)	Mean (SD)			
Average Pain	3.0/10 (1.6)	0.90/10 (0.9)	2.1 (*)	0.88, 3.32	1.7
Worst Pain	6.8/10 (1.5)	2.9/10 (2.3)	3.9 (*)	2.08, 5.72	2.0
Kujala Scale	86.4/100 (6.9)	90.8/100 (5.4)	4.4	-10.22, 1.42	0.1
Peak KFLEX	36.2° (5.3)	32.5° (4.2)	3.7°	-1.08, 8.48	0.78
Peak HFLEX	26.7° (9.3)	23.1° (4.9)	3.6°	-3.83, 11.03	0.51
Peak HADD	15.6° (3.5)	13.2° (5.4)	2.4°	-2.15, 6.95	0.54
Peak CLPD	4.3° (2.7)	2.8° (2.4)	1.5°	-1.05, 4.05	0.59
Peak HIR	9.1° (7.7)	4.0° (2.9)	5.1° (*)	-0.71, 10.91	0.96

Pre and post retraining means, standard deviations, mean differences, 95% confidence intervals and effect sizes

Key: (*)=mean difference exceeds MDC; SD=standard deviation; CI=confidence interval; HADD=hip adduction; HIR=hip internal rotation; CLPD=contralateral pelvic drop; KFLEX= knee flexion; HFLEX= hip flexion.

Table 3

Participant	Peak KFLEX at Follow Up	Peak HADD at Follow Up	Peak HIR at Follow Up	Peak KFLEX at Follow Up	Baseline Step Rate	Step Rate % Increase	Average Pain at Follow Up (x/10)	Worst Pain at Follow Up (x/10)
1	↓	↓	↓???	↓	160	11.1%	1	6
2	↓???	↓???	↓???	↓???	172	2.3%	2	5
3	↓	↓???	↓???	↓	168	7.7%	0	0
4	↓???	↓???	↓???	↓???	164	8.9%	0	3
5	↓	↑???	↓???	↓	168	7.7%	0	0
6	↓	↓???	↑	↓	164	8.9%	2	2
7	↑	↑	↓???	↑	164	5.7%	0	0
8	↓???	↓???	↑	↓???	158	10.2%	1	4
9	↑	↓	↑???	↑	158	6.0%	2	4

Individual participant kinematic, spatiotemporal and symptom responses to retraining

Key: (*)=difference exceeds MDC; HADD=hip adduction; HIR=hip internal rotation; KFLEX=knee flexion; A-NRS= average pain; W-NRS=worst pain.

sEMG

One participant was found to have consistently corrupted sensor data throughout their trials and was therefore removed from the sEMG analysis. This resulted in a sEMG sample of 9 participants (6 females, 3 males). A mean of peak muscle amplitudes, in addition to an integral (amplitude x duration) of each decomposed signal were calculated for each muscle pre and post retraining. For mean amplitude, minimal changes post-retraining were identified for GMAX (d=0.02), GMED (d=0.07) and ST (d=0.05). However, for VMO, an increase in mean amplitude was observed post-retraining, associated with a medium effect size (d=0.53, 95% CI -0.09, 0.03). For muscle integral, a similar interaction was identified, with minimal changes seen post-retraining for GMAX (d=0.04), GMED (d=0.04) and ST (d=0.09). For VMO, an increase was observed, associated with a medium effect size (d=0.58, 95% CI -0.06, 0.02).

DISCUSSION

The results of this study suggest that a faded feedback protocol to increase running step rate by 7.5%, is feasible in a clinical setting. A mixed sex cohort was successfully recruited and a low dropout rate (n=1) was achieved. Furthermore, potential clinically relevant changes in both average and worst pain were identified post-retraining, suggesting that the intervention has potential efficacy and warrants further appraisal in an adequately powered RCT.

The mean reductions in both average and worst pain seen within this study are smaller than those identified by previous running retraining studies, (Noehren, et al., 2011; Roper, et al., 2016; Willy, et al., 2012) although no inference on average or worst pain as individual outcomes were made by these studies and the feedback employed was different. Further, both this feasibility study and the referenced works were essentially underpowered for all but the most preliminary of conclusions. When analysing the reductions in worst pain from this study, only 3/10 participants were asymptomatic at six-week follow up and just one participant had pain $\leq$ 3/10. This means that the 6 remaining participants would continue to be eligible for inclusion into a clinical trial using currently accepted criteria, (Crossley, et al., 2016) meaning that the intervention could be defined as unsuccessful in 60% of our cohort if using worst pain as the primary outcome.

A recent high quality RCT identified that a 7.5% step rate increase, with the option of transitioning to a forefoot strike pattern if deemed necessary, was no more effective than comparative education or exercise interventions. (Esculier, et al., 2017) When comparing the symptom reductions achieved in this study (6 week follow up) to the relevant time point in the Esculier et al RCT (8 week follow up), (Esculier, et al., 2017) both average and worst VAS are comparable for our step rate intervention compared to all 3 intervention groups (education, exercise plus education, running retraining plus education). It could be suggested that running retraining is in fact a form of load management or graded exposure, which may explain why it was found to be no more effective than education on training loads by Esculier et al. (Esculier, et al., 2017) However, Roper et al (Roper, et al., 2016) reported efficacy of retraining from rearfoot to forefoot strike running. Importantly, this retraining strategy produced larger pain reductions when delivered using a faded feedback protocol, over and above an equivocal progressive duration running protocol. This suggests that a form of feedback is required over and above a load management intervention where there is a clinical need. A further potential explanation for the more modest symptom responses to step rate retraining reported by Esculier et al, (Esculier, et al., 2017) is that feedback is likely to have needed to be subject or subgroup specific and not all participants will have a baseline step rate amenable to an increase.

Previous studies on running retraining have established a potential kinematic mechanism at the hip to explain their positive effects, specifically a 5˚ reduction in peak hip adduction. (Noehren, et al., 2011; Willy, et al., 2012) The results of this study are in line with this, identifying a smaller but still clinically meaningful mean difference of 2.4˚ that was associated with a moderate effect size (Table 2). Our mixed-sex sample could explain this smaller mean difference, as the previous work of both Noehren et al (Noehren, et al., 2011) and Willy et al (Willy, et al., 2012) purposefully recruited female participants with higher than average peak hip adduction, which may be more amenable to change. However, as our results have identified a reduction in peak hip adduction equivalent to a previous 7.5% step rate increase study in asymptomatic runners, (Willy, et al., 2015) it is suggested that a larger increase in step rate (10%) will result in greater reductions in peak hip adduction equivalent to those seen in asymptomatic runners (Heiderscheit, et al., 2011). A 10% step rate increase is known to reduce both patellofemoral joint stress (Willson, et al., 2014) and pain (Bonacci, et al., 2017) in runners with PFP, whereas a 7.5% step rate increase (Esculier, et al., 2017) resulted in non-significant changes in both peak patellofemoral reaction force and average patellofemoral loading rate in a recent RCT. Clinically, it may be sensible to start retraining with a more modest 7.5% step rate increase, increasing to 10% or greater if tolerated, especially in those with low baseline step rate.

In addition to reducing peak hip adduction, the results of this study have identified two novel potential kinematic mechanisms, being a reduction in both peak hip internal rotation and knee flexion. The identified mean difference in peak hip internal rotation of 5.1° is above the MDC of 3.7° reported by Noehren et al (Noehren, et al., 2010) and was associated with a large effect size (*d*=0.96). Peak hip internal rotation is associated with running related PFP (Neal, et al., 2016) and can result in increased patellofemoral joint stress by increasing contact pressures at the lateral patellar facet. (Salsich & Perman, 2007) Thus, given the plausibility for reducing hip internal rotation during running gait to favourably alter PFP symptoms and the size of the identified effect, one could argue that a clinically meaningful change has been identified.

A reduction in peak knee flexion of 3.7˚ is in line with the work of Lenhart et al, (Lenhart, Thelen, Wille, Chumanov, & Heiderscheit, 2014) who reported a reduction in peak knee flexion of 3.3˚ with a 10% step rate increase in a normative cohort. Within this musculoskeletal model, (Lenhart, et al., 2014) peak knee flexion correlates positively with patellofemoral joint force, indicating this finding may be clinically relevant. This effect is likely due to changes in patella contact pressures, as a subsequent modeling study reports that lateral patellar arthrokinematics were not significantly altered by a 10% step rate increase. (Lenhart, et al., 2015) At an individual level, kinematic changes seem to correlate poorly with symptom improvements post-step rate retraining (see table 3). For example, two participants (one male, one female) had an increased peak hip adduction post-retraining (see table 3), with both participants asymptomatic for both average and worst pain variables. For the female participant, the increase in peak hip adduction (6.6˚) exceeds the MDIC (2.6˚) and is thus less likely to be related to measurement error. Future studies should look to investigate alternative potential mechanisms of running retraining, such as kinetic changes, load management or graded exposure.

Previous observational research investigating increasing step rate by 10% has identified increased quadriceps activation (Chumanov, Wille, Michalski, & Heiderscheit, 2012) comparable to the increase seen within this study. VMO activity is known to be altered in some individuals with PFP (Chester, et al., 2008) and VMO weakness is reported to correlate with lateral patella shift. (Sakai, Luo, Rand, & An, 2000) Whilst this study design prohibits inference of causality, this sEMG finding may be associated with the reduction in pain seen post-retraining.

The lack of change in mean gluteal EMG identified by this study is perhaps not surprising given the work of Willson et al, (Willson, et al., 2011) who report no differences in mean gluteal sEMG when comparing female runners with PFP to matched controls. Willson et al (Willson, et al., 2011) do however report that female runners with PFP demonstrate a shorter GMED activation window and delayed onset prior to foot contact in females with PFP. Additionally, Willy & Davis (Willy & Davis, 2013) reported earlier GMED activation and an increased GMED activation duration in a small case series of 2 female runners with PFP post-mirror running retraining. Combined with findings from our study, this indicates that changes to gluteal muscle activation patterns rather than magnitude may provide mechanistic explanation for the reduction in pain. Further research is needed to explore this and a limitation of the current study is the fact that the sEMG were not synchronised to the kinematic system, meaning not all variables of interest from the previous literature could be investigated.

<u>Future Directions</u>

Based on the results of this feasibility study, a future RCT should look to compare a step rate intervention against an exercise therapy control and investigation of effects to long-term follow up (~12 months) is advocated. Future work on running retraining should seek to use a faded feedback protocol, as it appears to result in superior outcomes. Recruitment of participants with a step rate of <160 (>1 SD below the mean of this cohort) who are more likely to be amenable to step rate retraining or stratifying outcome analysis by baseline cadence is worth considering – a strategy that would require greater samples but produce more generalisable findings. Sub-group analysis by baseline kinematic variables associated with PFP such as hip adduction may also be indicated, though kinematic variables do not appear to be sensitive to predicting those who may respond to a step rate intervention.

Whilst this feasibility trial was not powered apriori to investigate these effects, a post-hoc calculation using the mean difference of both average and worst pain revealed that a sample of 10 participants is adequate to investigate symptom changes post-step rate retraining with adequate statistical power (α=0.05, β=0.20). It is therefore advisable that future trials adhere to the so-called rule of 10, recruiting 10 participants per individual variable investigated to minimize risk of bias (Peduzzi, Concato, Kemper, Holford, & Feinstein, 1996) 10% of the biomechanical data in this study was lost due to data corruption and it is advisable that this be factored in to any sample size calculation for mechanistic outcomes in future studies.

Comparing the results of this study to the previous work on running retraining proved challenging given the heterogeneity of pain outcomes collected. It is advisable that future work collects data on both average/usual and worst/running related symptoms to allow for more clinically meaningful comparisons. The mean difference in the Kujala scale identified falls well below the accepted MCID of 10 points (Crossley, et al., 2004) and given the high baseline scores seen in the population studied, a ceiling effect can be suggested. Future studies are advised to consider an alternative measure of subjective function, with the lower extremity functional scale (LEFS), used by previous studies, (Noehren, et al., 2011; Willy, et al., 2012) and the recently developed patellofemoral subscale of the Knee Osteoarthritis Outcome Score (KOOS), (Crossley, Macri, Cowan, Collins, & Roos, 2017) particularly worthy of consideration.

CONCLUSION

The results of this study confirm that increasing running step rate using a faded-feedback protocol is a feasible and effective intervention for use in a mixed sex UK cohort. Future studies should focus on investigating the long-term efficacy of running retraining in a cohort that have a clear treatment target (i.e. low step rate), compared to an appropriate control. A sample size of ten participants per group/variable is adequate to detect minimum clinically important differences with adequate statistical power. In addition to future work establishing efficacy, exploration of both forms of feedback and treatment mechanisms is encouraged.

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(1) Conflict of Interest

The authors declare that they have no conflicts of interest in relation to this study.

(2) Ethical Approval

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