Supplementary file 5 Biomechanical effects of increasing step rate

FINDINGS	LEVEL OF EVIDENCE
<u>Spatio-temporal</u>	
↓ foot contact time	Moderate (2 HQS [1 2] and 1 MQS[3]^)
↓ medial and central forefoot contact time	Limited (1 HQS[1])
↓ flight time	Very limited (1 LQS[4])
↓ centre of mass vertical displacement	Limited (2 MQS[5 6])
<u>Ground reaction forces</u>	
↓ peak vertical GRF	Limited (1 HQS[7], 1 MQS[6] and 1 LQS[8])
↓ VIP, VILR and VALR	Limited (1 HQS[9] and 1 MQS[10])
↓ VIP, VILR and VALR at one month follow up	Limited (1 HQS[9])
↓ anterior-posterior GRF	Limited (1 HQS[7] and 1 LQS[8])
↓ total lower limb stiffness	Very limited (1 MQS[6])
<u>Plantar pressures</u>	
↓ force time integral for the heel; and medial and central forefoot	Limited (1 HQS[1])
↓ pressure time integral for heel; and medial, central and lateral forefoot	Limited (1 HQS[1])
↓ peak heel and lateral forefoot pressure	Limited (1 HQS[1])
<u>Foot and ankle</u>	
↓ peak internal ankle dorsiflexion moment	Limited (2 LQS[8 11])
↓ ankle dorsiflexion at foot strike	Limited (1 MQS[12] and 2 LQS[3 4]^)
↓ ankle dorsiflexion at midstance	Limited (1 HQS[7])
<u>Lower leg/tibia</u>	
↓ peak tibial acceleration	Limited (2 MQS[13 14] and 1 LQS[4])
↓ tibial contact forces	Very limited (1 MQS[15])
↓ soleus muscle forces during stance	Limited (1 HQS[7])
↑ tibialis anterior muscle activity during late stance/early swing (30–50% GC)	Limited (1 HQS[16])
↓ tibialis anterior muscle activity during late swing/pre-activation (80–90% GC)	Limited (1 HQS[16])
↑ gastrocnemius muscle activity during late swing/pre-activation (80–100% GC)	Limited (1 HQS[16] and 1 MQS[3]^)
<u>Knee</u>	

↓ peak PFJ stress/load	Strong (3 HQS[2 7 17])*
↓ knee power absorption	Limited (1 HQS[9], 1 MQS[5] and 1 LQS[11])
↓ knee power absorption at one month follow up	Limited (1 HQS[9])
Conflicting findings related to knee flexion at foot strike	1 HQS[7] = ↑; 1 LQS[4] = no change
↓ internal knee extensor moment	Limited 1 HQS[2], 1 MQS[12] and 2 LQS[8 11]
↓ patellar tendon force in midstance	Limited (1 HQS[7])
↓ peak knee flexion	Moderate (2 HQS[2 18] and 1 MQS[5])
↓ knee flexion velocity	Very limited (1 LQS[4])
Thigh	
↓ quadriceps (vastii) muscle forces during stance	Limited (1 HQS[7])
↑ RF muscle forces during late stance/early swing	Limited (1 HQS[7])
↑ RF muscle activity during late stance/early swing (30–50% GC) and late swing/pre-activation (80–100% GC)	Limited (1 HQS[16])
Earlier onset of vastus lateralis	Very limited (1 MQS[19])
↑ hamstring muscle forces during late swing	Limited (1 HQS[7])
↑ hamstring (medial and lateral) muscle activity during mid-late swing (70–80% GC)	Limited (1 HQS[16])
Earlier onset of hamstrings (biceps femoris) prior to foot strike	Limited (1 MQS[19])
Hip	
↓ hip energy absorption	Limited (1 MQS[5] and 1 LQS[11])
↓ peak internal hip extensor moments	Limited (2 MQS[5 12])
↓ peak internal hip abduction and external rotation moments	Very limited (1 MQS[5])
Conflicting findings related to hip flexion at foot strike	1 MQS[12] = ↓; 1 LQS[4] = no change
↓ peak hip adduction	Limited (1 HQS[9] and 1 MQS[5])
↓ peak hip adduction at one month follow up	Limited (1 HQS[9])
↓ gluteal muscle forces during stance	Limited (1 HQS[7])
↓ peak forces of the adductor magnus, and piriformis during loading	Very limited (1 MQS[20])

↑ peak tensor fascia latae, gluteus minimus, rectus femoris, and adductor brevis forces during early swing	Very limited (1 MQS[20])
↑ gluteal muscle forces during late swing	Limited (1 HQS[7])
↑ GMax and GMed muscle activity during late swing/pre-activation (80–100% GC)	Limited (1 HQS[16])
Spine	
↓ peak sagittal L5-S1 moment during impact	Very limited (1 MQS[12])
↓ vertical reaction forces at L5-S1 and T12-L1	Very limited (1 MQS[12])
No change in lumbar kinematics at foot strike or peak loading	Very limited (1 MQS[12])

GC = gait cycle, GRF = ground reaction force, HQS = high quality study, LQS = low quality study, MQS = moderate quality study, VALR = vertical average loading rate, VILR = vertical instantaneous loading rate, VIP = vertical impact peak

***** Includes findings from PFP population in Willson et al[2]

^ Includes findings from Sheehan et al[3] who investigated downhill running

Table Biomechanical findings related to increased step rate

Study (year)	Study design	Sample	Outcome measures	Intervention	Significant Biomechanical results
Willy (2015)[9]	Randomised controlled trial Treadmill running at 3.3 m/s	30 healthy (16 M, 14 F) runners aged 18-35 and with elevated impact forces (i.e. VILR > 85 body weights/second) Running at least 11.3 km/week	VILR and VALR Peak hip adduction Knee power absorption (per step and accumulative)	Increase step rate 7.5% above PSR using mobile biofeedback 8 training runs using faded feedback	12/16 in intervention group met SR prescription 10/16 continued to meet SR prescription during 1 month follow up monitoring ↑ step rate (167 to 181) ↓ VILR (19%) and VALR (18%) ↓ peak hip adduction (2.9^0 after retraining and 2.5^0 at 1 month follow up) ↓ peak knee power absorption Significant changes for all variables maintained at 1 month follow up
Willson (2015)[17]	Randomised cross-over design Treadmill running at PRS (2.84 +/- 0.22 m/s)	20 healthy (10 M, 10 F) runners aged 18-35 Primarily RFS runners Running at least 16 km/week	Per step and accumulative PFJ-RF Per step and accumulative PFJ-S	6 conditions, including PSR and +/- 10% PSR – each combined with RFS and FFS pattern	↓ peak PFJ-RF (17%) and stance phase impulse (20%) ↓ accumulative PFJ-RF and PFJ-S Per step: Increasing step rate had a greater effect on ↓PFJ-S than transition from RFS to FFS (16 V 10%) Accumulative load: Transition from RFS to FFS had a greater effect on ↓PFJ-S than increasing step rate (10 V 7%)
Willson (2014)[2]	Randomised cross-over within participant	10 female runners with PFP and 13 healthy female runners	Peak PFJ stress, knee flexion and internal extensor	At least +/- 10% PSL	↓ peak PFJ stress, PFJ stress integral per step and per mile, peak knee flexion and peak internal extensor moment with increased step rate (i.e. reduced stride length) in both groups

	Over-ground running at 3.7 m/s	Running at least 10 miles per week	PFJ stress integral per step and per mile Contact time		↓ contact time with increased step rate (i.e. reduced stride length) in both groups
Lenhart (2014)[20]	Randomised cross-over within participant Treadmill running at preferred speed (2.81 +/- 0.38 m/s)	30 (15 M, 15 F) healthy runners Running at least 24 km per week	Hip muscle forces	+/- 10% PSR	↓ peak forces of the gluteal muscles, rectus femoris, adductor magnus, and piriformis during loading ↑ peak hamstring (biceps femoris and semimembranosus) during loading ↑ peak tensor fascia latae, gluteus minimus, rectus femoris, and adductor brevis forces during early swing with ↑ peak hamstrings and gluteal muscle forces during late swing with
Lenhart (2014)[7]	Randomised cross-over within participant Treadmill running at preferred speed (2.81 +/- 0.38 m/s)	30 (15 M, 15 F) healthy runners Running at least 24 km per week	PFJ forces Thigh muscle and tendon forces Lower leg muscle forces	+/- 10% PSR	↓ vasti, gluteal, soleus, and patellar tendon forces during stance ↑ rectus femoris forces during late stance/early swing ↑ peak gastrocnemius, hamstring and gluteal muscle forces during late swing ↓ peak patellar tendon force in midstance ↓ PFJ force, loading rate and impulse ↓ peak knee flexion and ankle dorsiflexion at midstance ↑ knee flexion at foot strike ↓ peak vertical GRF and anterior GRF

Connick (2014)[19]	Randomised cross-over within participant Treadmill running at 3.61 m/s	11 healthy male runners 10 km personal best times of 34.81 (3.12) minutes	Muscle activation patterns for BF, VL and Gastrocs Muscle-tendon lengths	+/- 4% and 8% of PSL	Earlier onset of BF and VL with increased step rate (i.e. reduced stride length) No significant differences were found for Gastrocs
Thompson (2014)[8]	Cross-over within participant Over-ground running at preferred shod (3.31 +/- 0.47 m/s) and barefoot (3.18 +/- 0.48 m/s) speed	11 (6 M, 5 F) healthy runners (participating in a minimum of 30 minutes physical activity, 5 days per week)	GRFs Hip, knee and ankle kintetics	+/- 5% and 10% of PSL while barefoot and shod	↓ peak vertical and anterior-posterior GRF with increased step rate (i.e. reduced stride length) regardless of footwear ↓internal knee extensor and ankle dorsiflexion moments with increased step rate (i.e. reduced stride length) regardless of footwear No difference in frontal or transverse plane moments with increased step rate
Wellenkotter (2014)[1]	Randomised cross-over within participant Treadmill running at preferred speed (2.75 ± 0.44 m/s)	38 healthy runners (19 M, 19 F)	In-shoe plantar loading Contact time	+/- 5% PSR	↓ total foot peak force with increased step rate ↓ force time integral for the heel; and medial and central forefoot with increased step rate ↓ contact time whole foot; and medial, central lateral forefoot; but not the heel with increased step rate ↓ peak heel and lateral forefoot pressure with increased step rate ↓ pressure time integral for heel; and medial, central and lateral forefoot with increased step rate
Heiderscheit (2011)[5]	Randomised cross-over within participant Treadmill running at preferred	45 (25 M, 20 F) healthy recreational runners Running at least 15 miles per week for	Stance duration, COM vertical excursion Distance between COM and heel, and foot	+/- 5% and 10% of PSR	↓ COM vertical excursion, braking impulse, and peak knee flexion angle with increased step rate ↓ energy absorption at the knee with 5% and 10% increases to step rate Reduced energy absorption at the hip with

	speed (2.9 +/- 0.5 m/s)	at least 3 months prior to study	inclination angle at initial contact GRFs 3D kinematics and kinetics of the hip and knee		10% increases to step rate ↑ energy absorption at the hip, knee, and ankle with 10% reduction in step rate ↓ peak hip adduction angle with 10% increase to step rate ↓ peak external hip adduction and internal rotation moments with 10% increase to step rate
Chumanov (2012)[16]*	Randomised cross-over within participant Treadmill running at preferred speed (2.9 +/- 0.5 m/s)	45 (25 M, 20 F) healthy recreational runners Running at least 15 miles per week for at least 3 months prior to study	EMG of GMed, GMax, RF, VL, MHam, LHam, MG and TA	+/- 5% and 10% of PSR	↑ RF and TA activity during pre-swing/early swing (30–50% GC) ↑ MHam and LHam activity during mid-late swing (70–80% GC) ↑ GMax, GMed, RF and MG during late swing/pre-activation (80–100% GC) ↓ TA during late swing/pre-activation (80–90% GC)
Hobara (2012)[10]	Randomised cross-over within participant Treadmill running at 2.5 m/s	10 male healthy male runners	VIP, VILR and VALR	+/- 15% and 30% of PSR	↓ VIP, VILR and VALR with 15% increase to step rate but no further changes at 30%
Derrick (2000)[11]	Cross-over within participant Over-ground running at 3.83 m/s	10 male healthy runners	Tibial accelerations Stance times Sagittal plane kinematics (2D) Peak joint moments	+/- 10% and 20% PSL	↓ peak tibial accelerations with increased step rate (i.e. reduced stride length) ↑ leg stiffness ↓ stance times with increased step rate (i.e. reduced stride length)

			Energy absorption		↓ peak knee flexion with increased step rate (i.e. reduced stride length) ↓ peak internal hip, knee and ankle moments with increased step rate (i.e. reduced stride length) ↓ energy absorption at the hip knee and ankle with increased step rate (i.e. reduced stride length)
Clarke (1985)[4]	Cross-over within participant Treadmill running at 3.8 m/s	10 healthy runners Running 25-135 km/week	Tibial deceleration Sagittal plane kinematics (2D)	+/- 5% and 10% PSR	↓ peak tibial deceleration with increased step rate 20% shorter flight time and 3% shorter stance time with 10% increase to step rate No significant difference in sagittal plane kinematics with increased step rate, but a trend for reduced ankle dorsiflexion at foot strike ↓ knee flexion velocity with increased step rate
Hamill (1995)[13]	Cross-over within participant with balanced condition order Treadmill running at preferred speed (2.44 +/- 0.27 m/s)	10 healthy male runners	Tibial decelerations	+/- 10% and 20% PSR	↓ peak tibial deceleration with increased step rate
Mercer (2003)[14]	Randomised cross-over within participant Treadmill running at 3.8 m/s	10 healthy male runners	Tibial accelerations	+/- 15% PSR +/- 15% PSR (with fixed stride length) +/- 15% PSL with fixed step rate	↓ peak tibial deceleration with increased step rate ↓ shock attenuation (PTA) with increased step rate ↓ shock attenuation (PTA) with decreased stride length and fixed step rate

					No change to shock attenuation (PTA) with increased step rate and fixed stride length
Morin (2007)[6]	Randomised cross-over within participant Treadmill running at 3.33 m/s	10 healthy male runners	Contact time, vertical GRF, COM vertical displacement, and leg stiffness	+/- 10%, 20% and 30% PSR	↓ contact time COM vertical displacement with increased step rate ↑ leg stiffness with increased step rate ↓ peak vertical GRF with increased step rate
Seay (2008)[12]	Cross-over within participant Over-ground running at 3.8 m/s	10 healthy runners	Lumbar, hip, knee and ankle 3D kinematics and kinetics (L5-S1 and T12-L1)	+/- 20% PSL	No difference in lumbar kinematics at touch down or during peak loading ↓ vertical reaction forces at L5-S1 and T12-L1 during foot strike and impact with increased step rate (i.e. reduced stride length) ↓ peak sagittal L5-S1 moment during impact with increased step rate (i.e. reduced stride length) ↓ ankle dorsiflexion at foot strike with increased step rate (i.e. reduced stride length) ↓ hip flexion during impact with increased step rate (i.e. reduced stride length) ↓ sagittal plane internal extensor moments at the knee and hip during foot strike and impact with increased step rate (i.e. reduced stride length)
Edwards (2009)[15]	Cross-over within participant Over-ground running at preferred speed (4.4 +/- 0.5 m/s)	10 experienced male runners	3D kinematics and kinetics of the hip, knee and ankle Tibial forces	- 10% PSL	↓ peak tibial contact forces ↓ PSL of 10% reduced stress fracture risk by between 3 and 6%

Sheehan (2013)[3]	Randomised cross-over within participant Downhill (6^{o}) treadmill running at 3.0 m/s	10 healthy runners (5M and 5 F)	3D kinematics EMG of LHam, RF, LG and TA	+/- 15% PSR	↑ LHam and LG across stride ↑ LG activity in terminal swing ↑ ankle PF at foot strike ↓ contact time

* Based on same data set as Heiderscheidt (2011) – repeat results not summarised in Table

COM = centre of mass, EMG = electromyography, GC = gait cycle, GMed = gluteus medius, GRF = ground reaction force, LHam = lateral hamstrings, MG = medial gastrocnemius, MHam = medial hamstrings, PFJ = patellofemoral joint, PSL = preferred stride length, PSR = preferred step rate, RF = rectus femoris, TA = tibialis anterior, VIP = vertical impact peak, VILR = vertical instantaneous loading rate, VALR = vertical average loading rate, VL = vastus lateralis, 2D = two dimensional, 3D = three dimensional

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