

# Biomechanical Analysis of a Sport-Specific Lower Limb Strengthening Device

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Running Head: Biomechanics of Limb Strengthening Device

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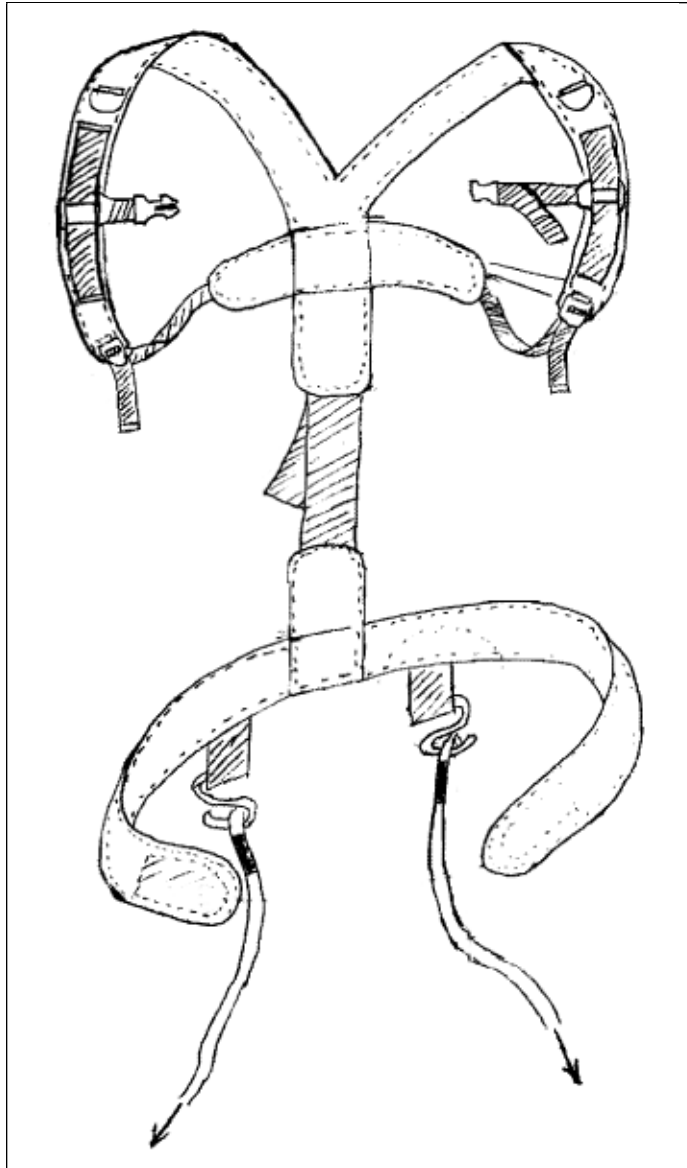
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## **Introduction**

Cartilage injuries are common in adults and present a significant challenge for clinicians. Once the articular surface is damaged, mechanical loading leads to accelerated joint wear and degeneration [1-3]. It is estimated that 80% of focal cartilage defects, if left untreated, will result in osteoarthritis, a degenerative joint disease characterized by both local cartilage pitting and global articular cartilage thinning [1, 4]. Osteoarthritis currently affects 21 million Americans and has been estimated to cost the US economy \$60 billion per year [1]. Interestingly, the majority of osteoarthritic lesions occur on the medial femoral condyle, largely due to chronic varus rotations, suggesting that correction of asymmetric loading in the knee joint may arrest damage progression. Recently, a device was developed by a former NBA player, Jonathan Bender, that can be used during specific athletic activities and incorporates a harness and two lengths of rubber tubing bands to apply a tensile forces between points just behind the hips and the posterior aspect of the ankles (Fig. 1). Executing normal motions while wearing this lower limb strengthening device requires concentric and eccentric contractions in opposing muscle groups, and may help strengthen the joints.

It has been reported that a population of children identified as athletically inactive exhibited 22-25% less articular cartilage than their athletically active peers and that appropriate training has can increase articular cartilage thickness and may promote healing of chondral lesions in adolescents [5]. This effect is believed to be mediated through increased tissue strain and fluid transport [6-8]. The lower limb strengthening device may also assist in recovery by improving joint stability. This mechanism also has the potential to distribute load more evenly between the medial and lateral condyles, potentially lowering the stress on the articular surfaces despite increasing the total force across the joint.



**Figure 1** – Schematic of the sport-specific lower limb strengthening device which consists of a harness that makes it possible to connect tension bands from the torso to the ankles.

Other athletic training exercises used to rehabilitate the knee joint post injury are primarily targeted to ligament injuries. The locations of maximum stress in the knee depends on the activity and for a given activity, vary significantly throughout the full range of motion and depend upon the muscle contraction. For instance, eccentric muscle contraction can produce significantly larger loads than isometric contraction, leading to greater forces in the knee [9, 10]. Various extension-flexion exercises also tend to localize the stress to a particular part of the knee. Isometric extension can create loads in the ACL up to 55% of body weight, while isometric flexion may generate loads in the PCL up to 400% of body weight with negligible loading of the

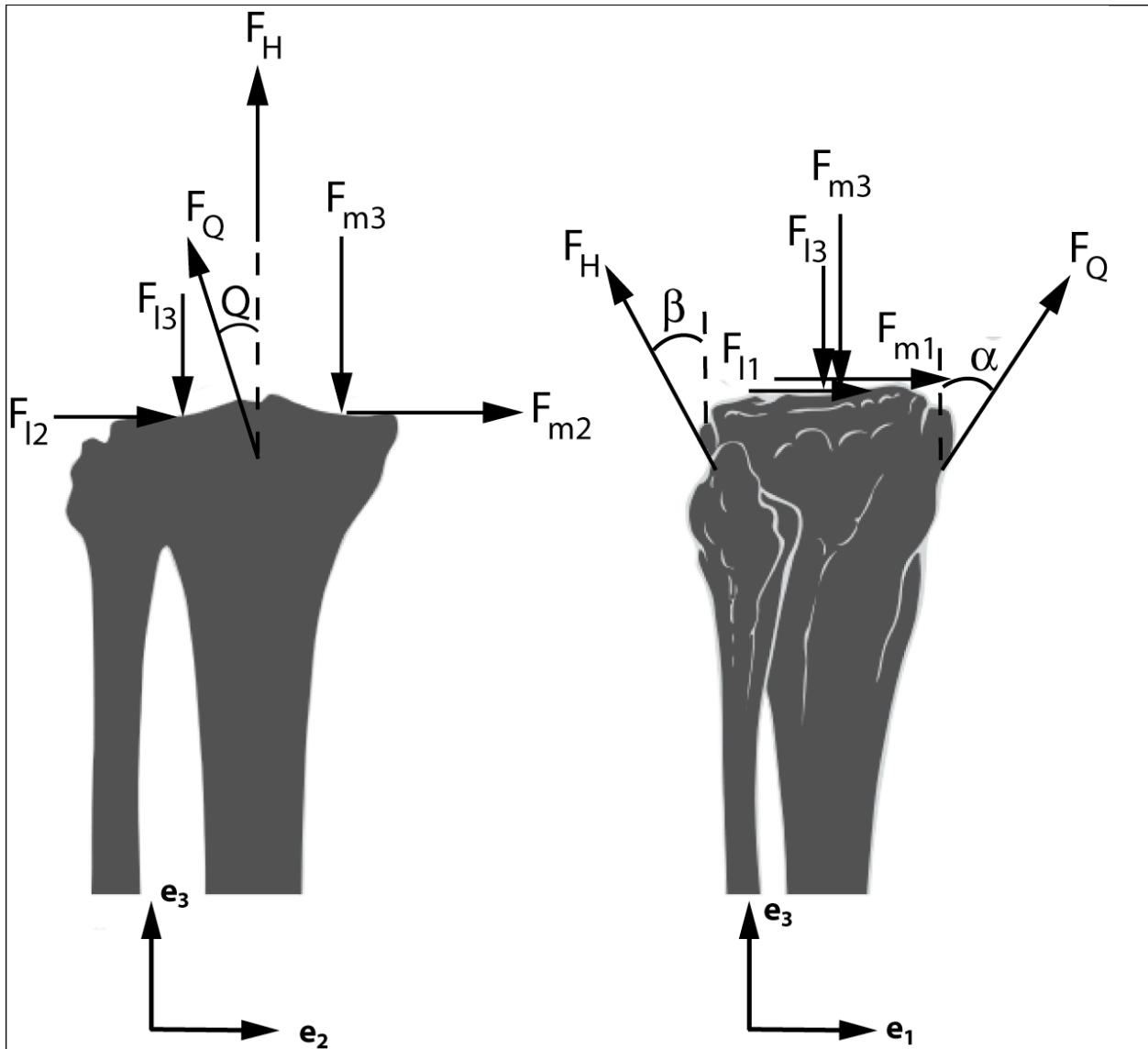
ACL [11]. Because the quadriceps muscles must work to overcome the moment generated by the tension bands during extension and the device also elicits eccentric co-contraction of the quadriceps during flexion in order to prevent rapid, uncontrolled movement, it is possible that the Bender Bands combine the benefits of several knee rehabilitation exercises. In order to develop a more precise understanding of the therapeutic value of the sport-specific lower limb strengthening device, a biomechanical analysis of their use was undertaken.

## Theory

Euler's equations were used to describe motion of the lower leg,

$$\begin{aligned}\sum \mathbf{F} &= m\bar{\mathbf{a}} \\ \sum \mathbf{M}_{\text{COM}} &= \mathbf{I}\boldsymbol{\alpha},\end{aligned}$$

where the vectors,  $\mathbf{F}$  and  $\mathbf{M}$  represent the forces and moments, respectively, acting on the lower leg during walking, running, and jumping motions (Fig. 2),  $m$  is the mass of the lower leg,  $\bar{\mathbf{a}}$  is the acceleration of the lower leg's center of mass,  $\mathbf{I}$  is the moment of inertia about the center of mass, and  $\boldsymbol{\alpha}$  is the angular acceleration. Because the accelerations were small compared to the muscle and joint contact forces,  $\bar{\mathbf{a}}$  and  $\boldsymbol{\alpha}$  were neglected.



**Figure 2** – Expanded view of the force model for the case where we allow for multiple contact points on the surface of the knee. The contact force,  $\mathbf{F}_C$ , was replaced by a medial contact force,  $\mathbf{F}_M$ , and a lateral contact force,  $\mathbf{F}_L$ , each with components defined relative to the co-rotational basis. The forces in the quadriceps and hamstrings are also included along with their relative orientations with respect to the tibia. Adapted from an illustration originally created by Patrick J. Lynch.

The vector equations were then cast in a simplified form,

$$\sum \mathbf{F} = \mathbf{F}_{\text{foot}} - m_j g \mathbf{E}_3 + \mathbf{F}_M + \mathbf{F}_L + \mathbf{F}_Q + \mathbf{F}_H = \mathbf{0}$$

where  $\mathbf{F}_{\text{foot}}$  is the ground reaction force on the foot,  $m_s$  is the mass of the shank (tibia and foot),  $\mathbf{F}_M$  and  $\mathbf{F}_L$  are the forces on the medial and lateral condyles, respectively, and  $\mathbf{F}_Q$  and  $\mathbf{F}_H$  are the forces in the quadriceps and hamstrings, respectively. In order to mathematically describe the forces, it is necessary to express them on either a fixed Cartesian basis,  $\{\mathbf{E}_1, \mathbf{E}_2, \mathbf{E}_3\}$ , or a coordinates system that moves with the tibia,  $\{\mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3\}$ , which are related at any given instant by,

$$\begin{aligned}\mathbf{e}_1 &= \cos(\theta)\mathbf{E}_1 - \sin(\theta)\mathbf{E}_3 \\ \mathbf{e}_2 &= \mathbf{E}_2 \\ \mathbf{e}_3 &= \sin(\theta)\mathbf{E}_1 + \cos(\theta)\mathbf{E}_3\end{aligned}$$

The quadriceps and hamstring forces are given by,

$$\begin{aligned}\mathbf{F}_Q &= F_Q (\sin(\alpha)\mathbf{e}_1 - \sin(Q)\mathbf{e}_2 + \cos(\alpha)\cos(Q)\mathbf{e}_3) \\ \mathbf{F}_H &= F_H (-\sin(\beta)\mathbf{e}_1 + \sin(H)\mathbf{e}_2 + \cos(\beta)\cos(H)\mathbf{e}_3)\end{aligned}$$

where the angles,  $Q$ ,  $\alpha$ , and the respective moment arms are summarized in Table 1,  $H$  was assumed to be  $0^\circ$ , and  $\beta$  was assumed to be  $20^\circ$ .

**Table 1:** Geometric parameters for anatomical structures around the knee.

Anatomical Feature	Males	Females	Reference
Q angle ( $^\circ$ )	$11.2 \pm 3.0$	$15.8 \pm 4.5$	Horton and Hall, 1989 [12]
$\alpha$ angle ( $^\circ$ )	$2.6 - 135.7$ (17.5 - 22.8 at 31-50 $^\circ$ flexion)		Kellis and Baltzopoulos, 1999 [13]
PT moment arm (mm)	$36.9 - 42.6$		Kellis and Baltzopoulos, 1999 [13]
H moment arm (mm)	$20.5 - 29.9$		Kellis and Baltzopoulos, 1999 [13]

The forces on the medial and lateral condyles are easiest to describe on the co-rotational basis,

$$\mathbf{F}_M = F_{M1}\mathbf{e}_1 + F_{M2}\mathbf{e}_2 - F_{M3}\mathbf{e}_3$$

$$\mathbf{F}_L = F_{L1}\mathbf{e}_1 + F_{L2}\mathbf{e}_2 - F_{L3}\mathbf{e}_3$$

where the negative sign on the  $\mathbf{e}_3$  signifies that the joint is assumed to be in compression. To simulate jumps, jump stops, and running motions, it was assumed that the forces on the medial and lateral sides were proportional, *i.e.*  $\mathbf{F}_L = \lambda\mathbf{F}_M$ , where  $\lambda$  is less than unity for most activities. Provided there is little or no twisting of the knee joint, this assumption is expected to provide more physiologically accurate results than typical approaches which combine the shear loads on each side. In particular, the assumption of proportionality allows for a more realistic treatment of the moments caused by forces on the medial and lateral condyles.

## Methods

When combined into Euler's first and second laws, one obtains a set of six nonlinear algebraic equations that must be solved numerically. The only required inputs are the joint angles, muscle angles, and ground reaction forces.

**Table 2** – Estimate ground reaction forces (GRF) for various activities.

Activity	Peak Loads (multiples of BW)	Reference
Jump Stops	3.5 – 4.0 VGRF	Kernozek et al., 2008 [14]
Jump Stops	4.27 VGRF	Onate et al., 2005 [15]
Running	0.79 Lateral GRF	Munro et al., 1987 [16]
	0.25 Lateral GRF (Braking effect and propulsion)	
	1.7 Average VGRF	
	2.32 Peak VGRF	

## Results

As an example, we considered a jump-stop with a vertical ground reaction force (VGRF)

of 2.5 times body weight, a lateral ground reaction force of 0.8 times body weight and a sideways ground reaction force of 1/10 body weight. When the tibia makes an angle of 30° with the vertical, the presence of the tension bands causes an increase in the quadriceps force and a doubling of the force in the hamstrings. There is a negligible increase in the forces on the medial condyle of the knee, but a notable balancing of the forces on the medial and lateral sides.

**Table 3** – Joint reactions in response to a jump stop.

Variable	Stiffness of Tension Bands		
	k = 0 N/m	k = 100 N/m	k = 200 N/m
$F_{sm1}$	-600 N	-600 N	-600 N
$F_{sm2}$	1000 N	1000 N	1000 N
$F_{m3}$	8200 N	8400 N	8400 N
$F_Q$	8800 N	10,000 N	10,000 N
$F_H$	3000 N	4000 N	4000 N
$\lambda$	0.40	0.60	0.60

## Discussion

Taken together, these data suggest that the sport-specific lower limb strengthening device increases the necessary force in all the muscles surrounding the knee, while improving the load balance between the medial and lateral sides. This is beneficial because smooth motion of the leg requires concentric contraction of either the quadriceps or hamstring muscles and eccentric contraction of the opposing set, an excellent combination for strength training. Balancing the load across the knee joint should also be beneficial. More importantly, these changes occur without appreciable changes in the joint contact forces on the cartilaginous surfaces of the knee. While this analysis cannot address changes in form that occur after the bands are removed, it has been hypothesized that working with the device has the potential to train the leg muscles to balance the load on the knee joint.

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