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ORIGINAL RESEARCH

The crural interosseous membrane re-visited: Part II, new biomechanical concepts

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Abstract. Demonstrate movement of the Interosseous Membrane (IM) when tensile loading was applied to the Tibialis Anterior (TA) and Tibialis Posterior (TP). Postulate new roles for IM in running. Nine IMs were assessed by 2 examiners. Dissections exposed the TA and TP. Posterior IM was palpated under TP as tensile loading of TA applied. Anterior IM was palpated under TA, as tensile loading of TP applied. Tensile loading was measured via a spring scale attached to distal tendons of TA and TP. TA tensile loading caused movement of IM anteriorly. TP tensile loading caused movement of IM posteriorly. T-test revealed no statistically significant difference between two examiners. The IM moves when TA and TP muscles undergo tensile loading. Rapid TA contraction during running pulls on the IM, pre-stretching TP and resulting in a forceful TP contraction. The IM is an important factor in pre-stretching of TA and TP. Nerve endings found in IM in our previous publication can increase afferent signal input and coordinate muscle activation of anterior and posterior IM muscles; IM acts as both a tendon and ligament; IM can coordinate muscular activity at heel strike and toe-off; IM limits separation of the distal tibio-fibular joint at heel strike; IM attenuates vertical ground reaction forces.

Keywords. Biomechanics, elastin, interosseous membrane physiology, jogging.

Introduction

Previous research by Sarmiento et al. (1974) defined the mechanical role of the interosseous membrane (IM) as stabilizing the tibia and fibula. With tibial or fibular fractures, the IM helps to stabilize fractures (Minns et el., 1976). Christodoulou et al. (1995) demonstrated via sonography that the stabilizing function of the IM can be lost in ankle fractures, if the IM is torn. Additional functions of the IM include limiting movement of the proximal tibiofibular articulation (Vukicević et al., 1980), transmitting load to the fibula during gait (Wang et al., 1996; Skraba et al., 1984; Durkee et al., 2003) and load bearing during gait (Minns et el., 1976). The IM is included as part of the articulation between tibia and fibula (Dattani et al., 2008). Various ligaments help the IM in stabilizing the distal tibiofibular articulation (Norkus et al., 2001).

Previous authors have shown that there is some separation of the distal tibiofibular articulation when the foot is completely dorsi-flexed. This separation has been reported to be up to 2mm (Norkus et al., 2001; Katznelson et al., 1983; Taylor et al., 1992; Taylor et al., 1993; Brosky et al., 1995; Stiehl et al., 1990; Anderson et al., 1995). This separation demonstrates limited flexibility of the distal IM and tibio-fibular ligaments. When the foot is completely dorsiflexed, the talo-crural joint, or tibio-talar joint, is maximally compressed and is thus most stable (Turco, 1977).

Minns & Hunter (1976) demonstrated that the force required to rupture the IM fibers was over 20 times

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greater in the direction parallel to the IM fibers than in the direction perpendicular to the IM fibers. This has important implications for the forces placed on the IM during running.

In a previous study (Morley et al., 2019), the current authors looked at the histological and microscopic anatomy of the human crural IM. Results demonstrated that there were Ruffini corpuscles, free nerve endings and rarely, Pacinian corpuscles in the IM. It is believed that this was the first time that these receptors had been found in the IM. Ruffini corpuscles adapt slowly to continuous tissue deformation, low frequency vibration, joint movements and stretching of the skin (Guyton et al., 2011; Saladin, 2012). Free nerve endings can act as pain receptors, superficial mechanoreceptors and deep mechanoreceptors (Guyton et al., 2011).

With the new histological and microscopic anatomical findings in Part I of our study as a base, the purpose of this second study on the IM was to take a new look at biomechanical aspects of the IM and propose new theoretical considerations. A muscle contracting concentrically or eccentrically will exert a pulling force on its origin attachment. The tibialis anterior (TA) and tibialis posterior (TP) both have part of their origin on the IM. We wanted to determine if the pulling of the TA and TP on the IM, could be measured. It is hoped that our results and theoretical new roles of the IM in running will lead to a better understanding of the IM's role in tibiofibular stabilization, movement during gait and a possible role as a pain generator. If it can be demonstrated experimentally that movement of a muscle originating on the IM pulls on its antagonist (i.e., tensioning the TP tendon results in movement of the TA muscle and vice versa) then it is reasonable to hypothesize new roles for the IM in running. The fact that the TP and TA are involved in rapid plantar and dorsiflexion during running provides evidence to support our descriptions of new roles for the IM in running

Methods

Five embalmed cadavers were made available for dissection in the cadaver lab at the School of Chiropractic, University of Bridgeport. Bodies were purchased for dissection classes. Two were male and 3 were female. The ages were not provided. Due to this study using cadavers, IRB approval was not necessary.

An experiment was done to measure the accuracy of the force/linear movement accuracy of a spring scale that is designed for measuring weights. This was done away from the dissection lab. The spring scale was fastened to a piece of ¾ plywood via 2 C clamps. This apparatus was laid down horizontally. The tension hook was placed at zero. Distal to the zero point, marks of 5 and 10 mm were measured and marked. Then, mm points of 1, 2, 3, 4, 6, 7, 8, and 9 were made. The hook was then pulled until 1 kg was registered. This process was repeated for 2, 3, 4, 5, 6, 7, 8, 9, and 10 kg. Ink marks were made at each linear point corresponding with a kg measurement. The force/length test showed a linear relationship between kg and mm; 1 kg moved the spring 1mm, 2 kg moved the spring 2 mm, etc. The apparatus can be seen in Figure 1 (1 mm marks don't show up well in Figure 1).

Figure 1. Spring scale set-up for force/linear test.

Posterior and anterior IMs were made available for palpation as follows: 1) Removal of 1st and 2nd layers of posterior crural muscles exposed the TP, allowing for finger palpation of the posterior IM under the TP. While the posterior IM was palpated, tensile loading was applied to the TA tendon and measured via a spring scale. 2) The TA was exposed, allowing for finger palpation of the anterior IM under the TA. While the anterior IM was palpated, tensile loading was applied to the TP tendon and measured via a spring scale.

With the tendons of the TA and TP exposed, the hook on the inferior part of the spring scale was placed around one of the tendons. Pulling on the scale led to tensile loading of the tendon and muscle. Each TA and TP trial was repeated twice. If there was less than a 0.25 kg discrepancy between trials, the second trial was used. If the discrepancy was greater than 0.25 kg between the 2 trials, 2 new trials were done. The 0.25 kg discrepancy was an arbitrary figure used for repeating a trial. The inter-examiner results can be seen in Table 1.

Examiners said "there" when they felt the IM move away from their finger. As stated above, the second measurement was noted and recorded. There were 3 muscles that were too dehydrated to use, so we obtained 17 results instead of the expected 20. All movements were assessed independently by 2 examiners and their results were compared. A third examiner controlled the pulling of the spring scale and wrote down the two examiners' verbal responses. A graph of the two examiners results can be seen in Figure 2.

Results

Inter-examiner results via a t-test showed no statistically significant difference between the 2 examiners ($p = 0.23$). This can be seen in Table 1. Plotting the results shows good compliance between examiners. This can be seen in Figure 2.

No significant difference between examiners.

Table 1

Inter-examiner results of forces noted to cause IM movement.

Muscle Loaded N = 17	Cadaver ID	Examiner 1 Kg	Examiner 2 Kg
Rt. TA	79187	9	9
Rt. TP	79187	2.5	4
Rt. TA	75179	4	2
Rt. TP	75179	9	7
Lt. TA	75179	2	3
Lt. TP	75179	1.5	2.5
Rt. TP	75240	1.5	1.5
Lt. TA	75240	3	3
Lt. TP	75240	2	1.5
Rt. TA	75242	2	2
Rt. TP	75242	1.5	1
Lt. TA	75242	4	2
Lt. TP	75242	2	2
Rt. TA	82119	2	3.5
Rt. TP	82119	3	2
Lt. TA	82119	3	2.5
Lt. TP	82119	1	1
Mean		3.12	2.91
Std. Deviation		2.37	2.11

Note. T-test done comparing examiners. p = 0.23.

(N = number of subjects, 17; Rt TA = right TA; Rt TP = right TP; Lt TA = left TA; Lt TP = left TP)

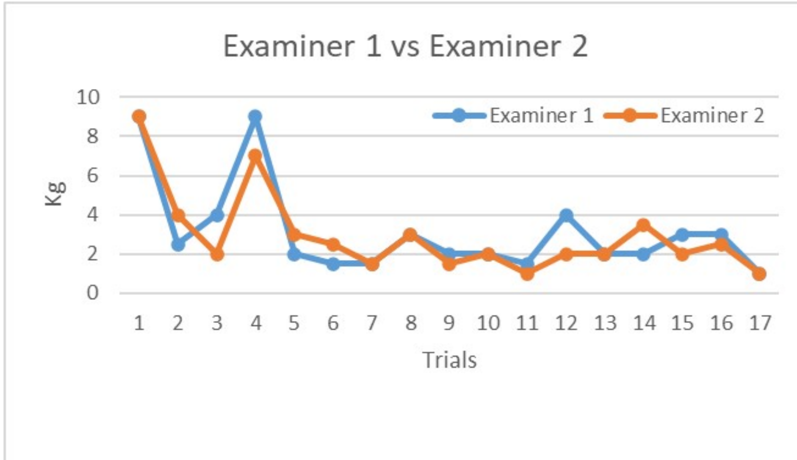

Figure 2. Plot of forces of 2 examiners causing IM movement.

Results obtained demonstrate that tensile loading of the TA and TP causes IM movement away from the palpating finger and in the direction of the muscle loaded in every trial.

Discussion

Muscles generally have their origins and insertions on bone. However, there are some muscles that have their origins in fascia: the platysma and gluteus maximus. The biceps brachii has its insertion on the fascia. The TA and TP have a significant part of their origins in the IM. When any muscle contracts concentrically, there will necessarily be a pulling or tension on their origins, whether the origins are bone or other tissue (Saladin, 2012).

Dorsiflexion of the foot is controlled by the TA, the extensor halluces longus (EHL), peroneus tertius (PT), and the extensor digitorum longus (EDL). Plantarflexion of the foot is controlled by the gastrocnemius, soleus, plantaris (PN), flexor hallicis longus (FHL), flexor digitorum longus (FDL), peroneus longis (PL), peroneus brevis (PB) and TP (Saladin, 2012).

The crural IM begins proximally at the interosseous crests of the tibia and fibula and extends all the way down to the distal tibio-fibular syndesmosis. It attaches itself between tibia and fibula, from proximal to distal. This attachment stabilizes the tibio-fibular relationship and separates anterior compartment muscles from posterior compartment leg muscles.

Dorsi-flexors and plantar flexors that attach to the IM include the EHL, EDL, PT and TA for dorsiflexion; FHL and TP for plantar flexion. In our experiment, we only investigated the TA for foot dorsiflexion and the TP for foot plantarflexion.

It is a given that a muscle contracting will pull on its origin. Our experiment was designed to determine if the effect of TA and TP tensile loading on the IM could be measured in cadavers. Our results confirmed that:

- Tensile loading on the tendon of the TP resulted in movement of the IM towards the TP, i.e., posteriorly
- Tensile loading on the tendon of the TA resulted in movement of the IM towards the TA, i.e., anteriorly.

With the foot in neutral, the IM is flaccid. It can be concluded that this is the normal state. Dissections of 18 cadavers have demonstrated this. Previous authors noted that the IM tightened with TP contraction and foot plantarflexion (Norkus et al., 2001; Weinert et al., 1973; Scranton et al., 1976). We propose that this slight flaccidity of the IM with the foot in neutral is an important factor in muscular control of the lower leg in running. The TP originates partly on the posterior IM. Thus, it can only tighten the IM by pulling it posteriorly. During jogging at approximately 3.67 m/sec, the time taken for the TP, a plantar flexor, to go from initial concentric contraction to maximal force is approximately 78 milliseconds (ms) (See Figure 3). This is calculated by taking time elapsing from the low point following impact peak to the active peak. During this brief time, the TA is being stretched rapidly by the plantar-flexing foot. The TA is also being stretched rapidly at its origin on the IM as the TP contraction rapidly pulls the IM posteriorly. We know from physiology that rapid pre-stretching of a muscle results in a more forceful contraction of that muscle (Guyton et al., 2011). Foot plantar flexion has finished at approximately 290 ms and a new foot cycle begins. Foot dorsiflexion and TA activity is calculated from 0 ms to the impact peak, about 37 ms. During this short period, the TA, which has been stretched rapidly, will elicit a more forceful contraction than would have occurred without the pre-stretching. This dorsiflexion activity will be completed in about 37 ms (See Figure 3). The TA will dorsiflex the foot rapidly and tighten or pull on the IM anteriorly. This causes the TP to be stretched rapidly during foot dorsiflexion. The TA's pull on the anterior IM will contribute to the rapid stretching of the TP. This will result in a more forceful TP contraction than would have occurred if the TP had not been rapidly pre-stretched. This forceful contraction of the TP is an important factor in elevating the body off of the ground during running.

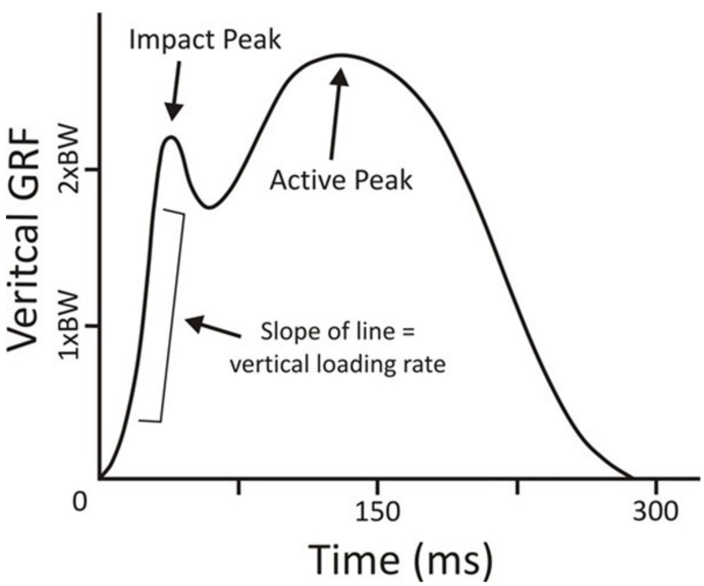

Figure 3. A typical vertical ground reaction force in running. BW = Body Weight Impulse (Impulse divided by Body Weight); Impact peak = Maximum force at Heel Strike; Low point following Impact Peak = Change from eccentric Quadriceps Femoris and Erector Spinae contraction to Concentric contractions; Active Peak = Maximum Forefoot Loading in preparation for Toe-off.

There is a reason for the difference in the pre-stretch times for the TA (78 ms) and the TP (37 ms). Bosco et al. (1981) discovered that a quicker muscle pre-stretch speed resulted in a greater jumping performance, a ballistic activity. Caserotti et al. (2008) discovered that the mechanical output of muscle is considerably improved when muscles are pre-stretched. Heel strike (HS) is associated with TA contraction and foot dorsiflexion. This is the deceleration phase of running. The build-up to Toe-off (TO) requires TP contraction and foot plantarflexion. TO necessitates lifting the body off of the ground and making it go airborne briefly. Thus, more muscle activity and more time are required for TO than for HS. More muscles are associated with TO than with HS. Pre-stretch time for the TP is quicker than for the TA. As per Caserotti et al. (2008), a quicker pre-stretch time results in a stronger contraction; the TA is pre-stretched 1.86 times longer than the TP.

The role of the proximal IM in rapidly stretching the TP and TA during running is a function of it being an origin for both muscles. The distal IM has a different function. Figure 3 shows the vertical ground reaction force (VGRF) associated with running. The first peak, called the impact peak, is about 2.2 times the body weight of the subject. This impact peak is generated the moment that the heel strikes the ground in running. At heel strike, the talus is forced superiorly into the ankle mortise joint and thus causes a slight separation of the distal tibia and fibula. This separation occurs because the IM and supporting ligaments are capable of stretching slightly due to elastin content. This mechanism involving the IM is designed not only to limit separation of the distal tibia-fibula articulation but also to partly attenuate the VGRF and thus transfer less VGRF to the knee. Other joints proximal to the knee do the same thing so that by the time the VGRF reaches the skull, it is considerably attenuated, protecting the brain from trauma. It is the thickness of the distal IM that we reported in our first study, that is one mechanism protecting harmful VGRFs generated during running, from reaching the brain.

We propose that the human crural IM acts as both a ligament and tendon, with the distal IM acting as a ligament (attaching bone to bone, i.e., distal tibia to fibula) and the proximal IM acting as a tendon (attaching muscle to bone, i.e., parts of origins of TA and TP to tibia and fibula). As a muscle contracts, tendons transmit the force to its bony insertion, allowing for muscle contraction and joint movement. Ligaments prevent excessive or abnormal joint movements. They attach bone to bone and can stretch and recoil to allow joint movement to occur (Rumian et al., 2007). Previously, the current authors (Morley et al., 2019) reported that the thickness of the distal IM was greater than that of the proximal and middle IM: 280 μm proximal, 290 μm middle, 370 μm distal. This finding is important because it is at the distal tibial-fibular area where there is a slight separation of the tibia from the fibula at heel strike. Strong ligamentous support is needed to minimize this separation and prevent injury. The distal IM acts as a ligament. It is attached between 2 bones (tibia and fibula) and limits their separation during running.

Elastin and collagen are the two important constituents of ligaments and tendons, with elastin allowing for deformation and collagen providing strength. Henninger et al. (2015) measured the response of ligaments to tensile and transverse forces and concluded that, although comprising only 4% of the weight of ligaments, elastin supported up to 30% of tensile stress under uniaxial strain and up to 70% of transverse stress under uniaxial strain. Zitnay & Weiss (2018) stated that elastin made up between 1-4% of the dry weight of tendon, but 4-9% of the dry weight of ligament. They also pointed out that elastin fibers are found between and alongside of collagen fibers. Results from our previous paper demonstrated that the percentage of elastin fibers between the two layers of collagen and inside the collagen fascicle layer was 10.1 +/- 0.5% and 2.2 +/- 0.1% respectively ($P<0.001$). Based on the percentage of elastin that we found in the IMs, it would seem that the entire IM acts as a ligament. However, as Rumian et al. (2007) pointed out, individual ligaments and tendons have unique properties reflecting their adaptation to a specific role. The specific role of the proximal IM is to serve as an origin point for the TP and TA and transmit the force of contracting muscle to the tibia and fibula, which is what a tendon does. In order to do this, the IM, which is flaccid with the foot at rest, must become tight. This is explained below.

In a previous study by the current authors (Morley et al., 2019), it was shown that the IM is a 2 layered structure, interspersed with collagen and elastin fibers.

Earlier, we cited Henninger et al. (2015) and Zitnay & Weiss (2018), who reported on the essential role of elastin in supporting tensile and transverse loading. The stress/strain characteristics of the IM were measured by Minns & Hunter (1976), who demonstrated that the IM could withstand more stretching before rupture in the transverse direction than in the longitudinal direction (40.5% ± 7.1 vs 7.7% ± 2.1 respectively). However, it required more loading to rupture fibers in the IM in the longitudinal direction than in the transverse direction (920 kg/cm ± 205 vs. 41 kg/cm ± 13 respectively).

In our previous article (Morley et al., 2019), we discovered that the 2 layers of the IM are interspersed with elastin fibers. Given the important role of elastin in tissue loading, the fact that it lies between the 2 layers of the IM may play a role in the tensioning of the proximal and middle IM during running. These are points for origins of the TA and TP. We pointed out earlier that the proximal and middle IM, as part of the origin of muscles involved in plantar and dorsiflexion of the foot, must assume some degree of rigidity in order for contracting muscles to be effective in moving the foot into plantar and dorsi-flexion. The constant and rapid contractions of plantar and dorsi flexion during running would necessarily place stress on the part of the IM that is the origin for the plantar (TP) and dorsi-flexor (TA) foot muscles. The pre-stretch/stronger concentric contraction is a logical explanation for tensioning the IM during running and thus providing a more solid point for the origin of the TA and TP.

As mentioned above, the 2 directions of loading or stress applied to the IM are longitudinal or tensile loading and transverse loading. Transverse loading is considered to occur between medial and lateral. However, we propose that transverse loading can also occur between anterior and posterior. This is reasonable since the pull of the TP and TA muscles occurs between anterior and posterior directions, i.e. when the TP contracts, it pulls the IM posteriorly and when the TA contracts, it pulls the IM anteriorly. Our previous discovery (Morley et al., 2019) of a relatively high elastin content between the 2 layers of the IM support this concept. When the TA contracts maximally at heel strike, the TP is rapidly stretched, contracting eccentrically. When the TP contracts maximally just prior to toe-off, the TA is stretched rapidly and is contracting eccentrically. At these times, there would be pulling on both the anterior IM via the TA and the posterior IM via the TP. A 2-layer IM interspersed with a relatively high concentration of elastin fibers interspersed with collagen fibers, would allow for the simultaneous anterior and posterior pulling on the IM without tearing it, i.e., the 2 layers of the IM could stretch slightly due to elastin fibers between the layers. Simultaneous anterior and posterior pulling on a 1-layer IM might be more prone to IM damage.

Another consideration involving the IM is shear stress. It can occur when there is movement along a plane in opposite directions (See Figure 4).

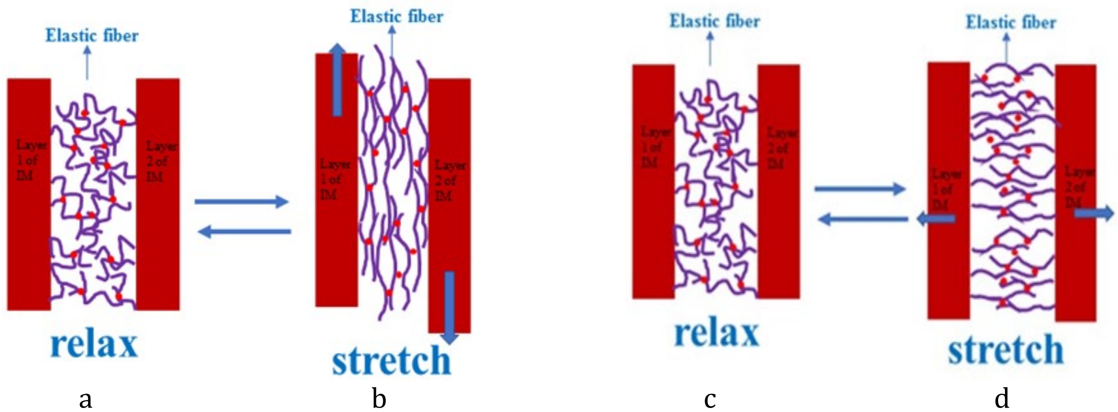

Figure 4. Elastin fibers in a relaxed state (a), under shear stress (b), again in a relaxed state (c), stretched by pulling on each side of the 2 layers (d).

There is at least one time when shear stress could occur during running gait. Norkus & Floyd (2001), Weinert et al. (1973) and Scranton et al. (1976) reported that the contraction of the TP causes foot plantarflexion, inferior movement of the fibula and tightening or tension on the IM. The TP pulls posteriorly on the IM when contracting. The fibula moves downward with foot plantarflexion while the tibia does not. It is possible that there could now be shear stress between the 2 layers of the IM, i.e., the posterior IM is moving inferiorly with the plantarflexion of the foot and inferior movement of the fibula while the anterior IM is not moving or being pulled inferiorly. Future work will need to be done to see if there is indeed shear stress between the 2 IM layers. To the best of the authors' knowledge, this is the first time that the concept of potential shear force on the IM during running, has been discussed.

The width between the distal tibia/fibula space is less than the width of the proximal and middle tibia/fibula space. That is in line with results from our previous study (Morley et al., 2019), i.e., the distal IM is narrower than the proximal part. Our data showed that the proximal part was 3.6 times wider than the distal part. That means that the fibers of the distal IM are shorter than those of the proximal and middle IM. This makes it mechanically impossible for the proximal and middle tibia and fibula to separate as a result of the distal tibia and fibula separating minimally during heel strike while jogging.

During running, the normal pattern is heel strike, not midfoot or forefoot strike (deAlmeida et al., 2015; Larson et al., 2011). The talus is forced superiorly against the tibia at heel-strike. The lateral tubercle of the talus sits at an angle of approximately 50° to the ground and at heel strike forces the fibula to splay away from the distal tibia. This fibular movement is up to 3° (Arndt, 2007). The distal IM helps to limit this lateral fibular movement, thus exhibiting its ligamentous activity. Because the distal third of the tibio-fibular-IM complex is narrower and straight and the upper two-thirds of the tibio-fibular-IM complex is wider than the lower third, heel strike cannot bring the upper two-thirds of the IM to maximum medio-lateral stretch.

The IM along with other anatomical structures, has been considered as one cause of medial tibial stress syndrome (MTSS), more commonly known as shin splints. In general, older literature did not show much support for this (O'Donoghue, 1984; Kues, 1990). One exception was an article by DeLacerda (1980). He had female students participate in a 14-week program of running and/or calisthenics performed on a hard surface. Subjects who developed MTTS were evaluated to determine which muscle activity provoked MTSS pain. The muscles overwhelmingly involved in reproducing MTTS pain were the TA and TP.

More recently, Tweed et al. (2008) identified a propulsive gait as a contributing factor in MTSS. This is a failure of normal heel strike runners to complete the normal HS to TO pattern. This can result in a more vertical lifting of the body as opposed to the normal forward propulsion. It is conceivable that a weak TA could affect pre-stretching of the TP and thus affect lifting of the body off of the ground at TO.

Future Research

We anticipate doing another study looking for nerve receptors in the IM. The follow-up study will concentrate on the parts of the IM that attach to the tibia and fibula. These attachment sites are under greater mechanical stress and logically would be expected to have more neuroreceptors. We will also be looking for nociceptors in an attempt to determine whether the attachment site of the IM could be a source of pain associated MTSS. Interestingly, Rosati & Medina (1987) stated that the IM does not insert directly into the tibia and fibula, but into the periosteum. Periosteal tissue is well supplied with nociceptors, and it will be intriguing to discover whether neuroreceptors and nociceptors are found at the osseous attachment sites of the IM.

One important area that we want to investigate in the future involves fascia and its possible functional link with the IM during gait. It is well established that fascia surrounds muscle and there are links between deep fascia and muscular fibers. Fascia is also involved in coordinating synergistic muscle activities over several joints (Stecco et al., 2011; Stecco et al., 2013). Because of the relationship of fascia and agonist and antagonist muscles elsewhere in the body, it will be important to determine the relationship, if any, between foot dorsi and plantar-flexor muscles, fascial connections and how the IM might be involved.

Applications in Sport

A major role of the posterior crural muscles in running is to lift the body off of the ground. A weak TA may not pre-stretch the TP sufficiently to elicit a strong TP concentric contraction. This could affect lifting the body off of the ground and negatively alter running mechanics. Thus, there may be an optimum anterior/posterior crural muscle ratio as there is for the quadriceps and hamstrings. Athletic trainers, physiotherapists and team doctors need to consider this.

Because neuroreceptors were found in the IM previously, there may be a number of nociceptors located at the osseous attachment sites of the IM (Morley et al., 2019). This could be a source of medial tibial stress syndrome (shin splints). Further research is needed to investigate this.

Conclusions

This paper has shown that the results of our first study underpin the practical and theoretical roles of the IM in running that were discussed. We devised a successful method of assessing movement of the IM in coordination with tensile loading of the TA and TP.

Several concepts we discussed appear to be new:

1. the proposal and evidence that the IM acts as both a ligament and tendon
2. the rapid anterior and posterior pulling on the IM during running results in pre-stretching the TA and TP and a more forceful concentric contraction
3. transverse loading of the IM could occur in the AP direction as well as in the medial to lateral direction
4. the IM appears to act as an attenuator of ground reaction forces.

A sound rationale has been given for the IM tightening in both dorsi and plantarflexion, in order to provide tight origins for the TA and TP to act and to pre-stretch muscles. This is the first time that this has been proposed to the best of the current authors' knowledge. These points will hopefully lead to further research on the IMs role in locomotion.

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Author Contributions

Conception and design, or analysis and interpretation of data: All authors.

Drafting the article or revising it critically for important intellectual content: All authors.

Final approval of the version to be published: All authors.

Ethical Approval

Due to this study using cadavers, ethical approval was not necessary.

Conflicts of Interest

The authors declare no conflict of interest.

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