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MECHANISMS FOR RUPTURED ACHILLES TENDONS: WOMEN'S GYMNASTICS

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Original article *DOI: 10.52165/sgj.17.3.355-372*

Abstract
The purpose of this study was to characterize the unusual take-off techniques demonstrated during tumbling take-offs on a spring tumbling strip (STS) and to assess the potential causes of these techniques and their possible contributions to Achilles tendon ruptures. A survey study of women's collegiate gymnasts showed an alarmingly high 17.2% prevalence of ruptured Achilles tendons (Bonanno, Cheng, Tilley, Abutalib, & Casey). Twelve highly trained female gymnasts from USA Gymnastics voluntarily participated. The take-off was captured (2D) via high-speed video (500 fps). An accelerometer (1D) was placed under the STS take-off position (1000 Hz). Reflective markers were placed on the toes, heels, ankles, knees, hips, torso center, shoulders, elbows, wrists, hands, and the apices of the head. Lower extremity angles were of primary interest. Two take-off trials were cross-correlated and analyzed. Results indicated an unusual and unexpected "secondary knee flexion" during take-off. Knee angle changes indicated that take-off actions were not simple eccentric knee flexion followed by concentric knee extension. The observed motions are heretofore undocumented. During the period from heel contact to heel departure, the gymnasts' ankles reach extremes of dorsiflexion at approximately the same time that their knees are extending, and the STS reaches its lowest position of descent. We speculate that the gymnasts may be readjusting muscle stiffness, reacting to a sudden intermediate vibration of the STS, or showing an artefact of the rearward rotation of the entire body about the feet. The observed actions may contribute to Achilles tendon injury.

Keywords: *tumbling take-off, injury, safety.*

INTRODUCTION

Modern artistic gymnastics for women consists of competition on four events – vault, uneven bars, balance beam, and floor exercise - and a summed score from these events (i.e., "all around"). The floor exercise event consists of rhythmic dance movements and tumbling skills performed to musical accompaniment (International Gymnastics Federation, 2000). Floor exercise tumbling includes skills such as cartwheels, handstands, handsprings, and forward and backward somersaults. Historically, the floor exercise event has been performed on a variety of surfaces, ranging from grass to hardwood gymnasium floors to the current spring floor apparatus (Davis, 1974; Girginov & Sandanski, 2004; Price, Keeney, Giallombardo, & Phillips, 1959). A ubiquitous tumbling skill in modern floor exercise is the rearward somersault (i.e., salto) following a take-off from a back handspring (i.e., flic-flac) or from a skill called a round-off. The take-off is performed as an explosive jump from two feet and is one of the most explosive and powerful skills in tumbling.

The incidence of Achilles tendon tears or ruptures has recently increased, with approximately 17.2% of U.S. collegiate gymnasts suffering such injuries during their training and competitions (Bonanno et al., 2022). Achilles tendon ruptures are particularly devastating, usually requiring surgery and extended rehabilitation (Kerr, Hayden, Barr, Klossner, & Dompier, 2015; J. Leppilahti, Karpakka, Gorra, Puranen, & Orava, 1994; Juhana Leppilahti, Puranen, & Orava, 1996; W. A. Sands, 2000; Taylor, Simon, & Feibel, 2009). This injury often plagues the very best gymnasts, particularly those of African descent and those performing the most daring skills (Bonanno et al., 2022). Moreover, the reported injury incidence is highest during floor exercise, particularly during rearward take-offs for somersaults, and in competition (Kerr et al., 2015; J. Leppilahti et al., 1994; Juhana Leppilahti et al., 1996; W. A. Sands, 2000; Taylor et al., 2009).

There is a paucity of information on the interactions between the gymnast and the spring tumbling apparatus. Developmental trends in rearward tumbling take-off and somersault skills have roughly paralleled apparatus enhancements, increasing skill difficulty by incorporating springier take-off and landing surfaces (Federation Internationale de Gymnastique, 1989). The body interface between the gymnast and the sprung tumbling surface is the foot. The primary motion at the ankle during take-off is dorsiflexion followed by plantarflexion in an explosive stretch-shortening cycle (M.F. Bobbert, Gerritsen, Litjens, & Van Soest, 1996; M. F. Bobbert & van Ingen Schenau, 1988; Bosco et al., 1982; Komi, 2000). The most involved ankle and foot anatomical structures are the triceps surae muscle group and the Achilles tendon. The gymnast's knees should flex, absorbing the impact, and then extend via the knee extensor muscles into the take-off (McNeal, Sands, & Shultz, 2007).

Rearward tumbling take-offs are brief (approximately 120-165 ms)(Dworak, Twardowska-Januszonek, Wojtkowiak, & Maczynski, 2006). While a typical standing countermovement jump often requires approximately 250 ms or more (Schmidtbleicher, 1992). The lower extremity engages several two-joint muscles in concurrent and countercurrent motion. The two joint muscles of concern for this study were the gastrocnemius. The gastrocnemius has an origin at the medial and lateral condyles of the distal femur and an insertion at the posterior superior calcaneus. The elapsed times of tumbling take-offs are short, but the forces experienced tend to be high, perhaps among the highest in sport. Peak ground reaction forces per foot in the vertical direction on landing a double backward somersault have ranged from 8.8 to 14.4 times body weight in the vertical direction, 5.3 to 8.8 times body weight in the anterior-posterior direction, and 0.9 to 2.1 times body weight in the medial-lateral direction (Panzer, Wood, Bates, & Mason, 1988). Of course, forces observed during landings are mirrored mainly by similar force magnitudes at take-off (Hay, 1973). However, the vast majority (85.7%) of tumbling Achilles tears occur during take-off (Bonanno et al., 2022). The large forces, in addition to the brevity of their applications, indicate that joints, muscles, and connective tissues must be extremely strong (Bruggemann, 2005). Unusual or inappropriate lower extremity positions and motions, when combined with high-impact forces, can increase the risk of lower extremity injury (Bieze Foster, 2007). However, there are numerous anecdotal accounts of Achilles tendon ruptures from seemingly normal activities.

The competitive spring floor apparatus surface dimensions are 12 m x 12 m (W. A. Sands, Cunningham, Johnson, Meek, & George, 1991). Smaller spring tumbling strips (STS) are primarily used for training tumbling skills in floor exercise. Spring tumbling strips are assembled by linking standard spring floor panels to provide a long tumbling surface that accommodates a run-up and a series of tumbling skills, usually ending with a flight skill to a soft-landing mat or foam pit (W. Sands, Cunningham, Johnson, Meek, & George, 1988). Spring floors and tumbling strips utilize coil springs, closed-cell foam blocks, wood and fiberglass laminate panels, and other materials as the elastic component under the spring panels. The goal of these elastic components is to create a rebound surface that promotes high flight trajectories while providing a forgiving landing surface (Gormley, 1982; Janssen, 2007; Paine, 1998; Paine, Self, & Major, 1996; Wilson, Neal, & Swannell, 1989). A stiff foam is laid on top of the STS panels, accompanied by a thinner carpet layer (3.1 to 5.1 cm in total thickness). The spring floor, like a trampoline, must achieve a compromise among elasticity, stiffness, and stability (Gormley, 1982).

The purpose of this study was to characterize and assess the interactions of tumbling take-off techniques on a spring tumbling strip (STS) and to explore potential relationships between these techniques and injury risk, with the aim of reducing injury risk. The benefits of the information gained from this study may include improved spring floor designs, a deeper understanding of take-off mechanics, and insights into the interactions between the gymnast and the spring floor. These benefits may progress to the point of developing effective Achilles tendon rupture countermeasures.

Figure 1. Underside of a spring floor panel using steel coil springs.

METHODS

Twelve United States junior-level female National Team and aspiring National Team members (mean ± SD: age 12.2 ± 1.2 y; height 143 ± 8.3 cm; mass 37.0 ± 8.3 kg; training age 5.7 ± 1.7 y) volunteered to participate in this study held at a national team training camp. This group was chosen because they were young, strong, and light, thereby reducing the risk of injury during the study. Conventional coaching wisdom indicates that lighter gymnasts are less likely to be injured and achieve higher competitive scores (Armstrong & Relph, 2021). This study was approved by the Institutional Review Boards of Eastern Washington University and East Tennessee State University for the study of human subjects. This study was conducted at the USA Gymnastics, Women's National Team Training Center, Huntsville, TX, USA.

Skills and Tumbling Apparatus

Athletes performed either a round-off, back handspring (flic-flac), backward layout somersault, or a round-off to backward layout somersault on an STS (American Athletic, Inc., Ames, IA., USA). The STS apparatus consisted of 12 wood and fiberglass laminate panels (1.23 x 2.44 x 0.013 m) held together at the long edges by metal fasteners. Each panel had 32 cylindrical coil springs placed evenly in 37 cm squares attached to the undersurface. The metal coil springs were 10.7 cm tall and 5 cm in diameter, with nine coils. Each spring was fastened to the panel's undersurface with round, plastic socket-like fasteners, held in place with wood screws. The top of the panels was covered entirely by Ethafoam™ closed-cell matting (416-745 Foam, 5.1 cm thick) and an adhered carpet surface. Figure 1 shows the spring configuration on the underside of a wood and fiberglass laminate spring-floor panel. The landing area was a 30 cm-thick open-cell foam (3.15 m x 3.7 m) skill cushion on top of a loose polyurethane foam pit (W. A. Sands, Cunningham, Johnson, Meek, & George, 1987).

Video Kinematics Data Collection

A high-speed black-and-white video camera (Photron™, Model 1280, Photron USA, San Diego, CA, USA) was placed perpendicular to the sagittal plane of motion. Video images were captured using PhotronTM software at 500 Hz (FASTCAM, Version 2.4.3.2, Photron, San Diego, CA, USA). The resolution of the video image was 1280 x 1040 pixels. Two-dimensional kinematics of selected body markers yielded the calculation of joint angles (ankle, knee, and hip) during the takeoff phase of the somersault. Data were obtained from markers on specific anatomical locations, particularly the lower extremity, using PEAK Motus™ software (Peak Performance Technologies, Motus Version 9.0, Centennial, CO, USA). Circular (2cm) reflective markers were placed on the left side on the 5th metatarsal, lateral malleolus, heel, lateral knee at the joint line, lateral hip at the greater trochanter, lateral torso at level of the xiphoid process and on the 12th rib at the inferior-lateral angle, shoulder, elbow, wrist, finger, and apex of the head. The tumbling direction was fixed so that the gymnast's left side faced the camera during the rearward somersault take-offs. Digitizing the left side of the athlete's body began before foot contact and continued until after foot departure. A quintic spline algorithm was used to smooth the digitized anatomical marker trajectory data (Woltring, 1985). Relative joint angles were identified for body segment positions throughout the impact phase from toe contact to toe departure. The angles of interest for this study were derived as follows (Figure 2): the knee-vertex and the two end-points were the hip and ankle, and the ankle–vertex at the lateral malleolus with two end-points at the knee and toe. The gymnast's center of mass was calculated using the parallel axis theorem (Hay, 1973) and a body segment model developed for female gymnasts by Kjeldsen (Kjeldsen, 1969; Plagenhoef, 1971). Two-dimensional calibration was performed using a rectangular calibration frame (1.00 m x 1.10 m) according to the manufacturer's instructions.

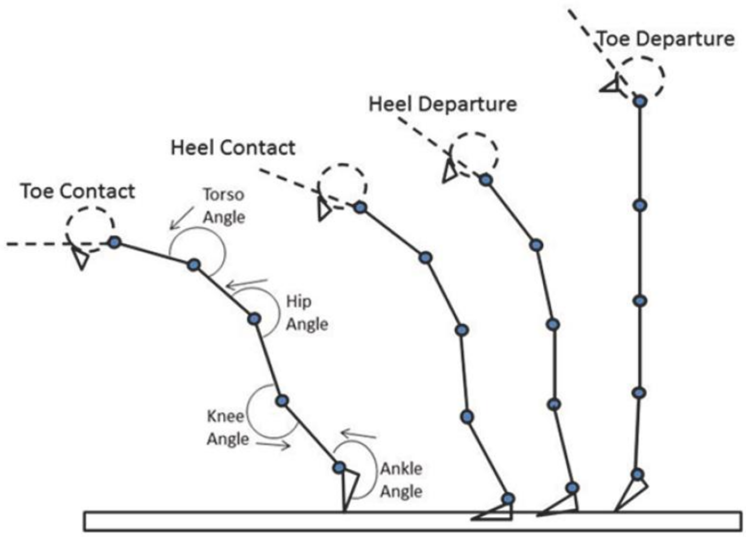

Figure 2. Diagram of relative angle determination and selected take-off positions relative to foot placements. The stick-figure representation of the gymnast moves from left to right. The primary focus of this analysis is the trajectories of the knee and ankle markers, as well as the corresponding knee and ankle angles.

Instrumentation

The STS was instrumented with a single-axis accelerometer (50 G, ICSensors, Milpitas, CA, USA) placed under the final spring panel of the tumbling strip and sampled at a rate of 1000 Hz. The accelerometer was adhered to the middle and bottom of the spring panel, 66 cm from the end. A 40 cm square was outlined by tape on top of the mat and carpet, with the accelerometer positioned at the center of the square on the panel's underside. The accelerometer was amplified using a custom instrumentation amplifier, and the analog signal was then passed to a Noraxon^{TM} analog-to-digital converter and a laptop computer for data display and storage. Accelerometer data were integrated from acceleration to velocity and then from velocity to displacement using the trapezoidal rule via MATLAB and Simulink software (The MathWorks, R2008b, Natick, MA, USA).

Procedures

Twelve gymnasts performed two trials of a round-off, back handspring (flic-flac), and backward layout somersault on the STS. One gymnast, who had suffered a previous arm injury that was resolving, elected to perform a round-off to backward layout somersault, thereby avoiding the back handspring. All gymnasts participated in a choreographed National Team warm-up lasting approximately 30 minutes before data collection. Then gymnasts performed a self-selected warm-up and familiarized themselves with the STS and take-off "target" area (taped square). The athletes were marked with reflective markers (2 cm diameter) at the sites noted above. Gymnasts then performed two trials of tumbling skills following a self-selected number of warm-up trials. Trials were repeated if the gymnast was unsatisfied with her performance or the gymnast failed to take-off within the taped "target" square. Athletes were instructed to perform the highest and most powerful layout somersault they could.

Skill performance start and end time information was obtained from an accelerometer (1000 Hz) and the high-resolution, high-speed video records (500 FPS). The video software included a magnification function that allowed for an enlarged view of foot contact events with the STS. The gymnast's body positions were digitized, stored, filtered, and used for further calculations of horizontal, vertical, and resultant displacements, velocities, accelerations, knee angles, and ankle angles. The same investigator performed all data reduction via digitization and event determination. Synchronization was based on visual inspection of toe contact and initial accelerometer motion detection.

Technique Performance – Two Knee Flexions

Figure 3 shows a composite view example of the first maximum knee flexion, the second maximum knee flexion, and the changes in lower extremity joint angles throughout take-off. Although some knee flexion is expected in a tumbling take-off, two knee flexions are unusual and do not appear to serve the explosive nature of the motion.

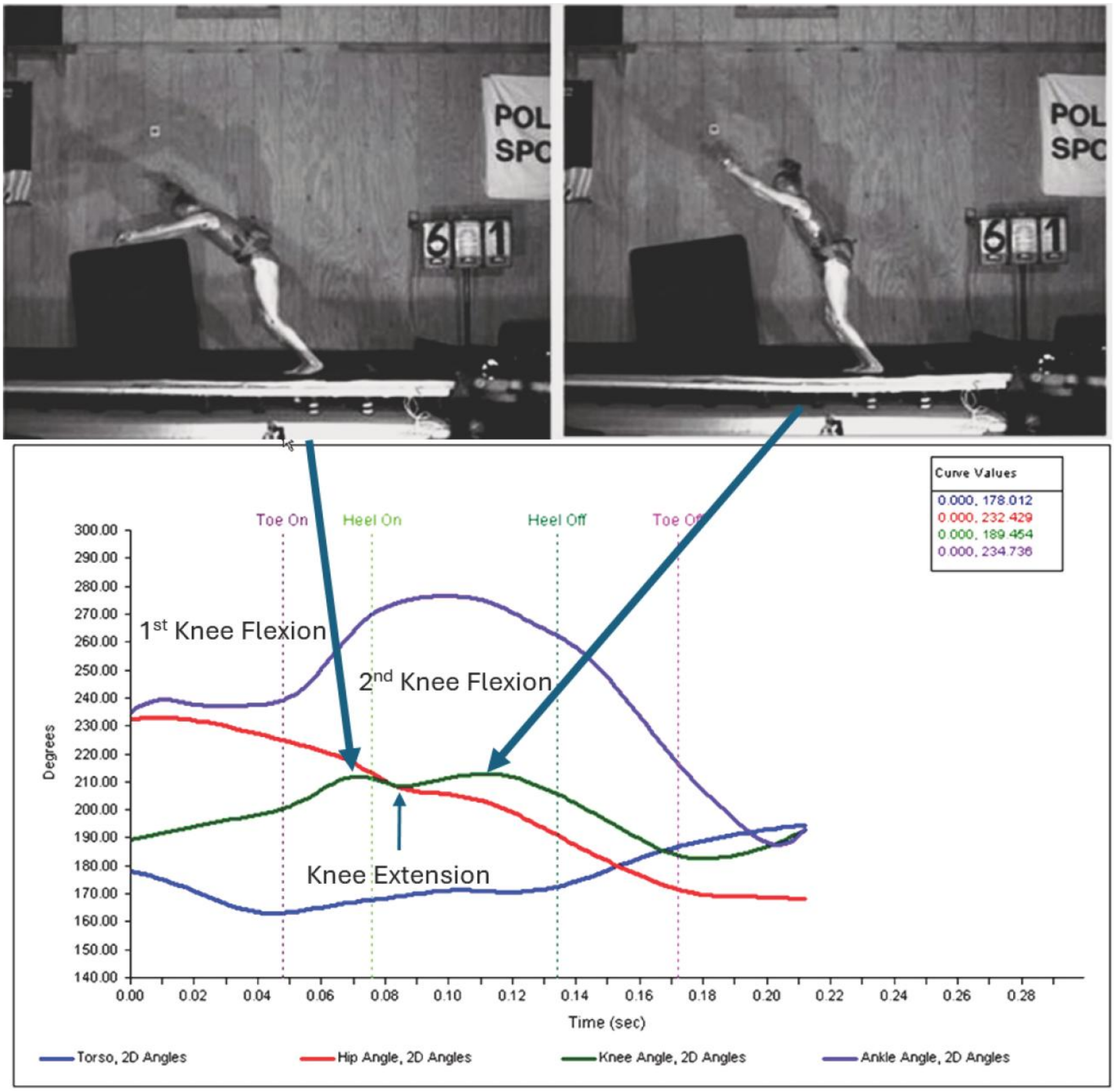

Figure 3. The top panel displays extracted video frames that depict the first and second knee flexion positions. The two knee flexion phases (bottom graph, green = knee angles, purple = ankle angles). The knee marker path trajectory exhibits a notable inflection as the gymnast performs eccentric knee flexion for impact absorption during the initial contact phase, followed by a slight knee extension. Finally, full knee extension occurs, allowing for take-off and a somersault.

Analysis

This study examined the potential relationship between technical factors and the risk of Achilles tendon rupture. As such, this study was hypothesis-generating rather than hypothesis-testing (Batterham & Hopkins, 2006; Levin & Marascuilo, 1977; McComas, 1997). We could not ethically induce an Achilles tendon rupture for evidence of technique and injury relations. Data are presented as descriptive statistics (mean ±SD). Each analyzed sample period was uniform for all athletes and began with the initial accelerometer data spike indicative of STS downward acceleration and corresponding feet impact. Visual inspection revealed that 150 ms was sufficient to characterize the entire take-off period, from toe contact to toe departure, for all gymnasts. Each gymnast performed two trials, which were combined into a single mean trend, sample by sample, across the entire take-off period (150 ms). Athlete kinematic data and STS acceleration data were also subjected to reliability analysis, with knee angle ($r = 0.95$-0.99) and ankle angle ($r = 0.98$-0.99) showing high reliability for sample pairs. Reliability of the trials' data was statistically significant for all athletes but one (11 of the 12 subjects, (500 Hz, $r = 0.64$ to $r = 0.94$) and moderate for one athlete ($r = 0.52$) (Hopkins, 2000). The athlete's data with the lowest cross-correlation and reliability values was eliminated from the dataset. Eleven subjects' performances were retained for further analysis.

Take-off data were also analyzed by viewing the correspondence of the movement pattern with the musculoskeletal pattern of countercurrent motion (Figure 4) (Luttgens & Wells, 1982). The location of the toe, lateral malleolus, and knee allowed the construction of a virtual triangle for further analysis of the knee angle. In contrast, concurrent motions link two joint muscles together such that the joint actions cooperate to maintain the lengths of the muscles involved during normal motion, and therefore, a higher tension position in their length-tension relationship (Hof, Van Zandwijk, & Bobbert, 2002; James, Sacco, Hurley, & Jones, 1994). Countercurrent motion at the ankle occurs when the gastrocnemius is stretched at the heel end by the foot's dorsiflexion and stretched from the knee end as the knee joint extension arises from the anterior quadriceps muscles. The stretch of the gastrocnemius and Achilles tendon, if excessive, may increase the risk of tendon rupture. (Luttgens & Wells, 1982).

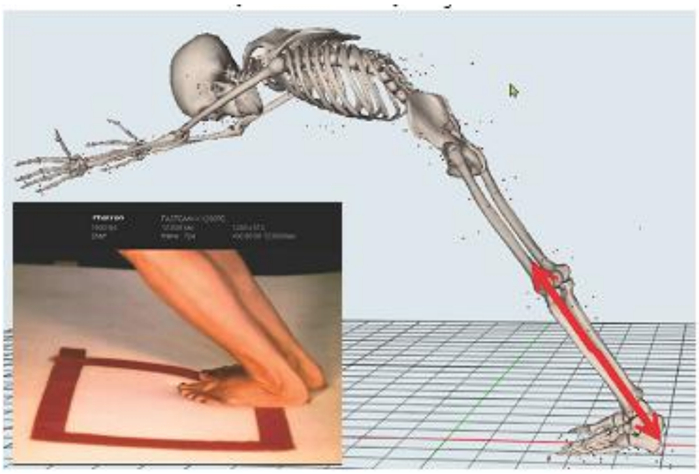

Figure 4. The large image shows a schematic skeleton with the gastrocnemius and Achilles tendon lines of pull as they are stretched. Inset image - Frame extraction from high-speed video showing extreme dorsiflexion during take-off. Countercurrent motion is displayed via the red arrows, indicating the opposing directions of the superior and inferior gastrocnemius and Achilles tendon. Note that this diagram was rendered in three dimensions while the kinematics were conducted in two dimensions.

RESULTS

The performances of eleven female gymnasts were analyzed for variables within the rearward tumbling take-off. An example of the angle changes of the knee and ankle is shown in Figure 4. Take-off and foot contact events were identified. Descriptive data were calculated and shown in Figure 5. Two of the eleven athletes performed the backward layout somersault take-off by moving their foot only slightly into dorsiflexion, thus avoiding heel contact with the STS. Foot contact times were: 0.033 s (SD = 0.005 s) from toe contact to heel contact, 0.044 s (SD = 0.011 s) from heel contact to heel departure, 0.050 s (SD = 0.009 s) from heel departure to toe departure. The mean and standard deviation of contact duration of the two athletes who did not touch their heels was 0.128 s (SD = 0.007 s). The total foot contact time for all athletes showed a mean of approximately 0.127 seconds.

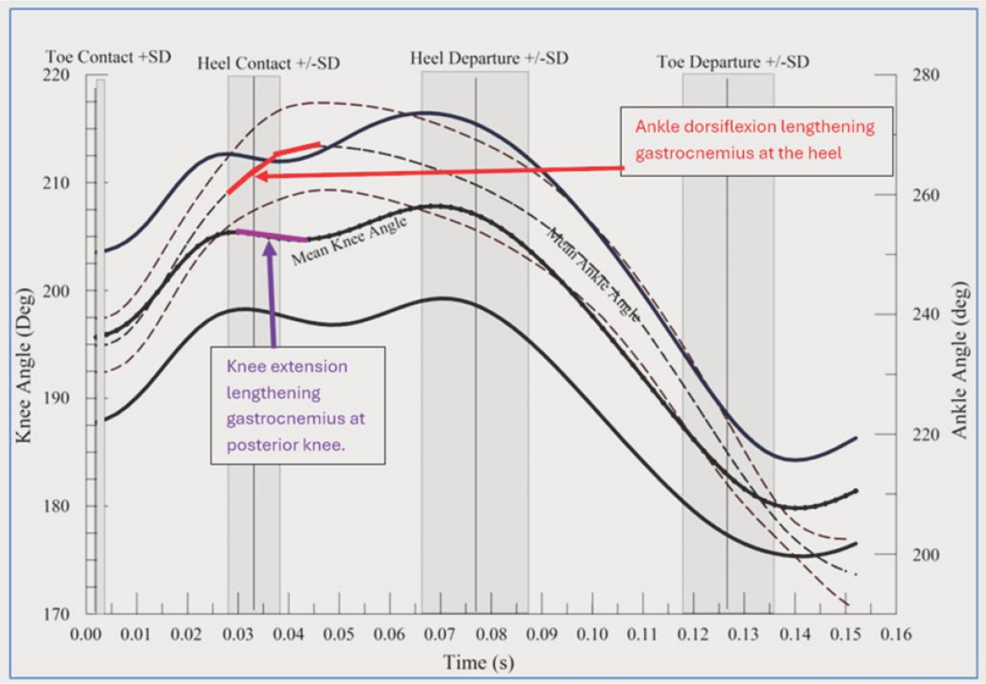

Figure 5. Means and SDs with a highlighted section showing the countercurrent motions at the knee and ankle. Note that ankle dorsiflexion increases in a vertical direction (up) on this graph, and knee extension angle increases in a vertical downward direction. Vertical lines depict different take-off events. The event “heel on” is coincident with the “bottoming” of the STS.

The incorporation of countercurrent motions (Gregoire, Veeger, Huijing, & van Ingen Schenau, 1984; Luttgens & Wells, 1982), as illustrated in Figure 4, is demonstrated in the example presented in Figure 5, where countercurrent motion is integrated into the take-off technique, which is currently limited. Rather than provide information in one or more tables, we elected to include most of the data in images of knee movements during a rearward tumbling take-off. As such, we have included many examples in Figure 6.

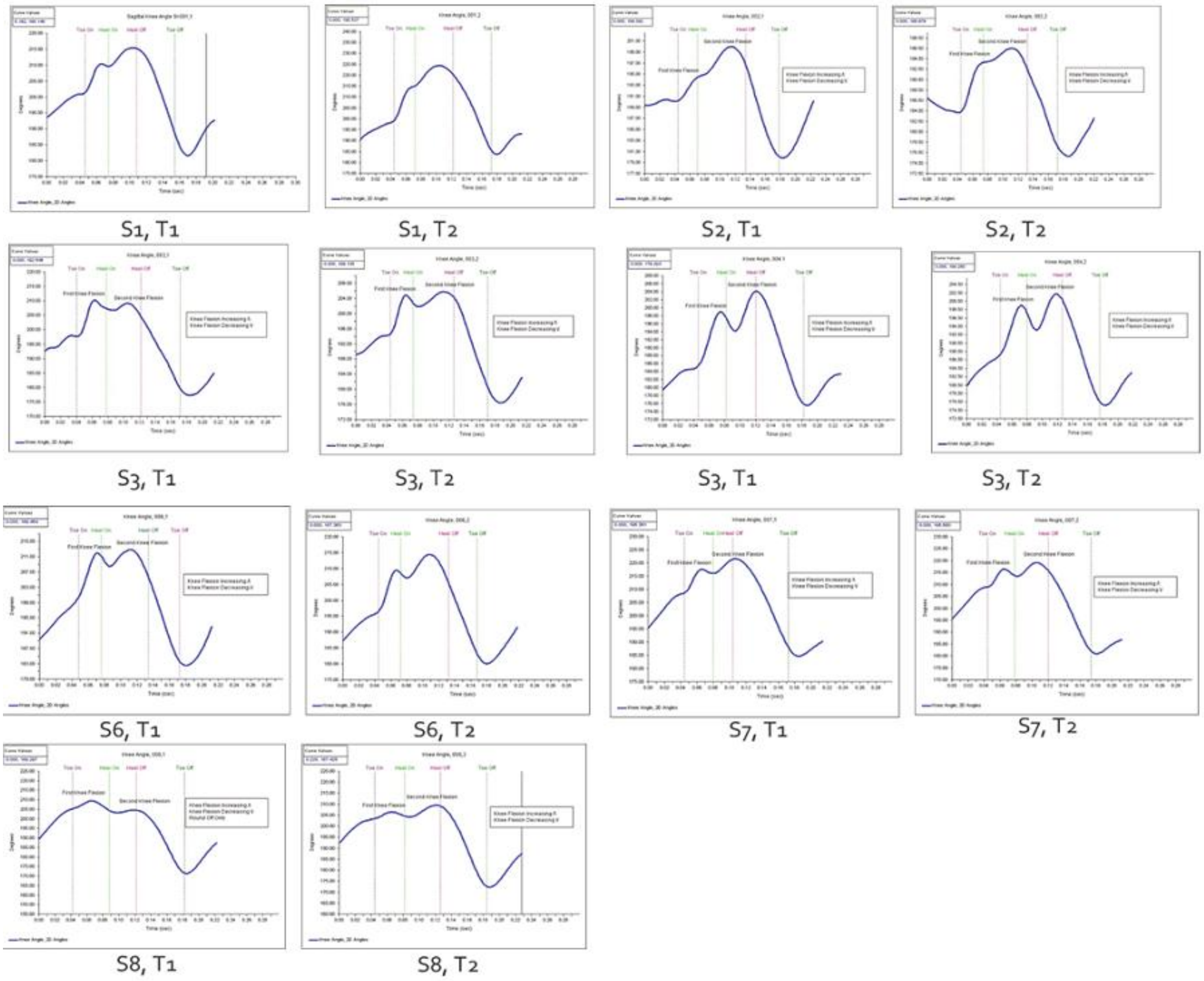

Figure 6. Images of many of the performance datasets with the two performance trials. Figure captions show the subject and trial numbers (e.g., Subject 6, Trial 1 = S6, T1). We attempted to include a variety of knee angle patterns. Note two knee flexion "bumps" in these data, further exemplifying this unusual but possible common technique that places the Achilles tendon at risk for rupture due to the rapid lengthening from muscle tension combined with a stretch at both ends created by the mechanics of countercurrrent motion. Moreover, the winding and unwinding of the spiral nature of the AT may result in a "shock" at the end of the unwinding.

DISCUSSION

Characterization of the lower extremity in the tumbling rearward take-off revealed an unusual and unexpected pattern of motion. The investigators have been unable to find research information that shows this phenomenon in the extant gymnastics literature. As such, the two knee flexion actions are puzzling and disquieting because we have demonstrated how mechanics can place the AT under excessive stretch. Unlike other tendons, the AT is commonly injured (Bojsen-Møller & Magnusson, 2015). The AT may have a relatively low margin for error, such that it commonly operates near its maximal tensile strength during regular movements (Bojsen-Møller & Magnusson, 2015). The most significant finding and unresolved question for this study were the reasons why these gymnasts flexed their knees twice or delayed extension. Moreover, is there a relationship between the unusual knee flexions and susceptibility to AT injury? Gymnasts in this study presumably flexed their knees to absorb the initial impact, then extended their knees, albeit momentarily, by varying amounts, and finally flexed their knees again immediately before a final knee extension and ankle plantarflexion that led to take-off and departure from the STS. Could this action involve the loading and unloading of the rotational actions (i.e., twisting) of the longitudinal segments of the AT, similar to a coiled material that unwinds and rewinds to control force (Bojsen-Møller & Magnusson, 2015; Edama et al., 2015)? The three longitudinal segments of the AT form a triple helix, arising from the medial and lateral gastrocnemius and the soleus, like the collagen fibers from which they develop (Bojsen-Møller & Magnusson, 2015; Edama et al., 2015). Multiple muscles with adjoining long tendons afford the originating muscles the ability to control tension further (Bojsen-Møller & Magnusson, 2015; Edama et al., 2015). Moreover, the AT segments also rotate internally, providing another means of controlling tendon tension by winding and unwinding at a micro-level (Bojsen-Møller & Magnusson, 2015; Edama et al., 2015). The AT main segments, when viewed from above, form a clockwise rotation classified into three categories (i.e., large twist, moderate twist, and small twist) (Bojsen-Møller & Magnusson, 2015; Edama et al., 2015; Edama et al., 2016). Could one of these categories be more susceptible to rupture than the others? It appears that the three main segments do not wind and unwind in unison, and the timing disparity may be involved in weakening the AT's structure (Bojsen-Møller & Magnusson, 2015; Edama et al., 2015). Most athletes exhibited two brief periods of knee flexion, or, more rarely, a short hesitation in knee extension that preceded the final take-off action. Could the brief knee extension that occurs, bordered by two knee flexions, provide the necessary time for the AT segments to wind or unwind? Neural activation of the longitudinal segments, working in concert or perhaps even at cross-purposes, is complicated and poorly understood, but may hold the key to understanding gymnastics tumbling technique and the sudden, excessive tension that ruptures the AT via slack in the segments and/or mistimed transfer of tension to the calcaneous (Bojsen-Møller & Magnusson, 2015; Edama et al., 2015; Edama et al., 2016). Experiments on cadaver ATs have shown that loads are handled heterogeneously (Bojsen-Møller & Magnusson, 2015; Edama et al., 2015; Edama et al., 2016).

Although the investigators have been unable to find prior evidence of this pattern of motion in related literature, one previous study of male national team gymnasts performing the same skill from the U.S. Olympic Training Center revealed the same motion pattern. A recent three-dimensional study (unpublished data) with female gymnasts again showed the same lower extremity movement pattern, as in this study – all athletes in these unpublished studies demonstrated two knee flexions and no hesitations. Why would anyone perform a jump by flexing their knees twice? The answer seems to be that they may have no choice. The twisting of the AT during loading may behave like twisted ropes, allowing the tendon to store strain energy that is later released when the "ropes" (i.e., tendon segments) unwind. This mechanism could also account for the pause (slight extension of the knee) during take-off.

One possible explanation for the two knee flexions is that the second flexion provides a means of regulating muscular stiffness of the lower extremity, particularly the triceps surae and quadriceps. Changes in muscular stiffness have been observed during drop jumps onto an elastic spring floor (Arampatzis, 2002; Arampatzis & Brüggemann, 1999; Arampatzis, Brüggemann, & Klapsing, 2000). An increase in leg muscle stiffness increases the transfer of energy to and from an elastic spring floor when performing drop jumps, and the loss of energy because of the viscoelastic surface of the spring floor was calculated at 24 ± 8.2% (Arampatzis & Brüggemann, 1999; Arampatzis et al., 2000; Arampatzis, Brüggemann, & Klapsing, 2001; Arampatzis, Stafilidis, Morey-Klapsing, & Brüggemann, 2004). Do gymnasts require one level of muscular stiffness during the initial, presumably eccentric tension, of the force absorption involved with the initial landing impact, and then follow the initial impact by adjusting muscle stiffness to maintain rigidity of the lower extremity and continue the take-off? Young and less skilled gymnasts are frequently observed flexing their knees with marked deceleration during rearward tumbling skills (W. A. Sands, 1984, 1994). However, the gymnasts in this study were highly trained and skilled. None would be considered novices.

Control of muscle stiffness during human hopping (i.e., jumping) has been postulated to occur from centrally controlled motor commands and stretch reflexes (Kuitunen, Ogiso, & Komi, 2011). A study of simple drop jumps from two heights (20 and 40 cm) revealed that maximal power was achieved with optimal leg stiffness values. The optimal stiffness of the lower extremity can be modified by instruction, muscle preactivation levels, and varying movement contexts (Arampatzis & Brüggemann, 2001). Activation of involved muscles may serve a crucial role in regulating vertical jumping via innervation onsets, durations, and magnitudes (M. F. Bobbert & van Zandwijk, 1999; McNeal et al., 2007).

Although all gymnasts performed ankle dorsiflexion, nine of the eleven gymnasts touched their heels to the STS, acceleration of STS nears zero, and velocity of STS remains relatively steady in a downward direction during this period. During the period from heel contact to heel departure, the gymnasts' ankles are reaching extremes of dorsiflexion at the same time the knees are extending, and the STS is reaching its lowest position of descent (Figure 4). In summary, at the end of the phase of heel contact to heel departure when the gymnasts' ankles are nearly maximally dorsiflexed, there is a brief pulse of STS acceleration, and the knees flex for the second and last time. Is the abrupt acceleration pulse of the STS linked to AT injury exposure? The gastrocnemius is a biarticular muscle with origins on the distal posterior femur and insertion into the common AT. During the heel departure period, the ankles were plantarflexing and knees were extending (Figure 4). Studies of ankle and AT forces have shown complex interactions that subject the tendon to significant linear and non-linear loadings (A.N. Arndt, Bruggemann, Koebke, & Segesser, 1999; A. N. Arndt, Komi, Brüggemann, & Lukkariniemi, 1998; Bojsen-Møller & Magnusson, 2015). Could the second knee flexion or hesitation be a protective reflex reducing the loads on the AT by altering force directions and magnitudes? Or perhaps the slight hesitation allows the longitudinal segments of the AT to reset for the high forces required to complete takeoff.

The STS may contribute to extreme mechanisms that could result in AT injury. However, an injury may require additional factors. For example, muscular fatigue may induce strain characteristics that exceed the capabilities of the triceps surae. In a study of female gymnasts executing 225 drop jumps across three sessions, totaling 675 jumps, the gymnasts demonstrated fatigue by experiencing increased accelerations during landings. The 675 jumps are an unrealistically high training load (B. Sands, 1984; W. Sands et al., 2019; W. A. Sands, Henschen, & Shultz, 1989; W. A. Sands & Major, 1991; W. A. Sands & Stone, 2006). The acceleration values were 136% of pre-fatigued values in the first fatiguing session, rising to 140% of non-fatigued landings during sessions two and three (Beatty, McIntosh, & Frechede, 2006). Gymnasts may not use their lower extremities symmetrically during a rearward tumbling take-off. In a study of drop landing forces from 30, 60, and 90 cm among 15 female gymnasts, the results showed that only two of the athletes demonstrated symmetrical ground reaction forces (i.e., peak forces bilaterally within 10%) (Beatty et al., 2006; Lilley, Bradshaw, & Rice, 2007). Tumbling take-offs have revealed differences in the temporal behaviors and magnitudes of the gastrocnemius and vastus lateralis muscles during backward take-offs, with the gastrocnemius activating before the vastus lateralis and exhibiting distinct activation patterns based on whether the take-off resulted in a twisting somersault, thereby altering the expected symmetry between the two legs (McNeal et al., 2007). Muscle sequencing, activation temporal characteristics, and magnitudes may be natural variation in human physical performance (Bates, James, & Dufek, 2004; Caster, Chen, Dufek, & Bates, 1994; Dufek, Bates, Stergiou, & James, 1995).

COUNTERMEASURES

Given that techniques and external forces displayed by these athletes may be unalterable, one is likely to conclude that external countermeasures are the only reasonable means of protection (i.e., bracing). The application of external means for AT rupture prevention has not gone unnoticed. Achilles and ankle taping by skilled athletic trainers has been used for decades (Figure 7). Unfortunately, standard taping techniques using athletic tape suffer from the athlete's body heat and sweat, reducing much of their bracing integrity within approximately 20 minutes after the tape is applied (Cupler, Alrwaily, Polakowski, Mathers, & Schneider, 2020). Moreover, despite the use of such taping measures, athletes still experience AT ruptures.

An external device invented and patented by one of the authors may provide a means of preventing AT injuries. The device is called a Safe-T-Strap and is applied to the foot and shank by the athlete, partner, or athletic trainer (Kling & Sands, 1980). This device is used to supplement the existing athletic taping (AT) by being placed in parallel to the tendon and secured with athletic tape (Figure 8). The Safe-T-Strap differs from standard AT taping approaches by providing a leather strap that serves as an additional form of AT.

Experience has shown that the detection of weakened or susceptible ATs has not been reliable. Coaches and medical professionals may choose to incorporate thermal imaging as a means of early identification of heat in the tendon complex (W. A. Sands, 2008, 2013; W. A. Sands, McNeal, & Stone, 2011).

Figure 7. Commonly used athletic taping to protect the AT.

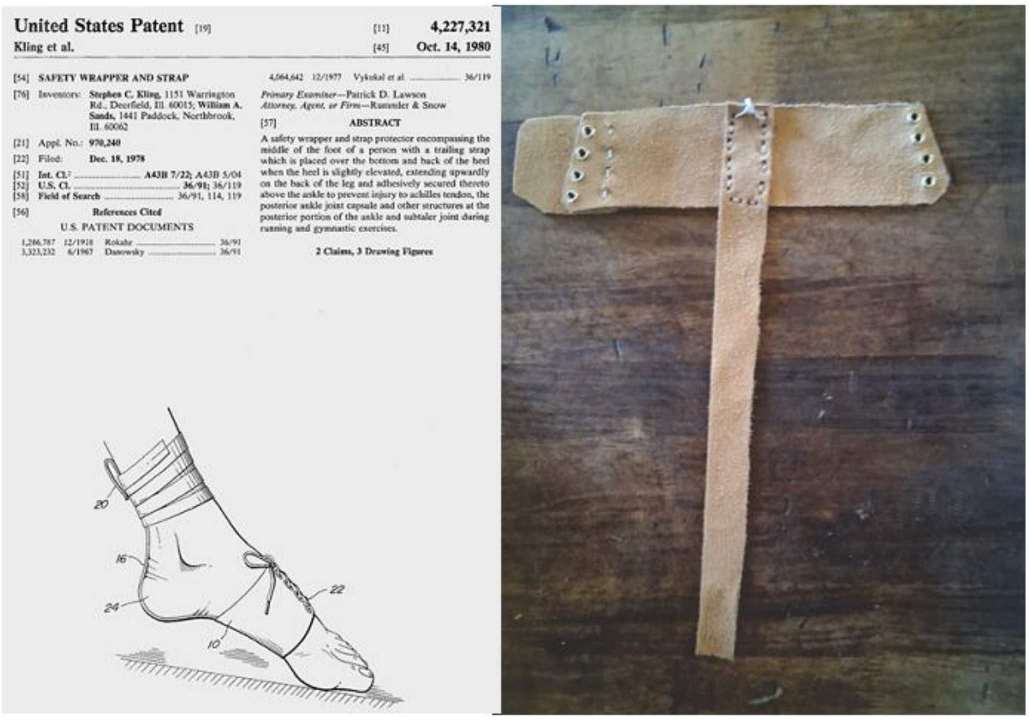

Figure 8. Patent document describing the Safe-T-Strap and a leather Safe-T-Strap by the first author.

The authors recommend the use of thermal imaging of the triceps surae and AT. Thermal imaging has been used in gymnastics to identify athletes with inflammation. One unpublished study showed that athletes with inflamed areas but no limiting symptoms approximately six months later developed limiting symptoms in all the identified areas (W. A. Sands, 2008, 2013; W. A. Sands et al., 2011). Figure 9 illustrates a female gymnast experiencing back pain and the corresponding heat signature of inflammation.

Figure 9. A female gymnast displaying the heat signature of low back pain. The two lighter areas correspond to the gymnast's pain.

Avoidance of some medications may be warranted to prevent weakening of the tendon connective tissue. There may be an issue with antibiotic medicines, specifically fluoroquinolones (Kaleagasioglu & Olcay, 2012; Melhus, 2005; Seeger et al., 2006; Tsai & Yang, 2011). This class of antibiotics has been linked to tendon rupture. If the athlete was using or had recently used this standard class of antibiotic medications, could the medication be at least partially responsible for a weakened athletic tissue (AT)? Wisdom should caution against this and other similar medications to prevent their impact on AT integrity.

CONCLUSION

Pragmatically, gymnasts do not produce aggregated or mean AT injuries. ATs are injured one at a time. Potential mechanisms warrant further investigation to ensure the safety of these young athletes. Most of these gymnasts, performing a tumbling rearward somersault take-off, presented an unusual and unexpected motion involving two knee flexions. Regardless of the specific pattern of knee motion, when the ankle is placed in extreme dorsiflexion, the tensile loads on the AT are incredibly high. The ubiquitous nature of knee motions observed with high-speed video and biomechanical analyses demands more explicit investigation. Is this unusual "jump" motion based on a shift in central control of muscle stiffness, the non-uniform vibration response of the elastic STS, or from some other source? Does the observed motion of the lower extremity contribute to the risk of injury to the AT? As an initial study of the phenomena described here, future research will be necessary to investigate the interactions between the gymnast and the tumbling apparatuses (W. A. Sands et al., 2013). In particular, the role of AT twisting may hold promise. The devastating nature of an AT rupture should motivate the scientific and medical communities to understand the potential roles of several mechanisms that could place the gymnast at increased risk of injury.

ACKNOWLEDGEMENTS

No conflicts of interest are noted.

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Article received: 25.6.2025
Article accepted: 17.8.2025