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Short communication

The jump shot – A biomechanical analysis focused on lateral ankle ligaments

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ABSTRACT

Handball is one of the top four athletic games with highest injury risks. The jump shot is the most accomplished goal shot technique and the lower extremities are mostly injured. As a basis for ankle sprain simulation, the aim of this study was to extend the ankle region of an existing musculoskeletal full-body model through incorporation of three prominent lateral ankle ligaments: ligamentum fibulotalare anterius (LFTA), ligamentum fibulotalare posterius (LFTP), ligamentum fibulocalcaneare (LFC). The specific objective was to calculate and visualise ligament force scenarios during the jumping and landing phases of controlled jump shots. Recorded kinematic data of performed jump shots and the corresponding ground reaction forces were used to perform inverse dynamics. The calculated peak force of the LFTA (107 N) was found at maximum plantarflexion and of the LFTP (150 N) at maximum dorsiflexion. The peak force of the LFC (190 N) was observed at maximum dorsiflexion combined with maximum eversion. Within the performed jump shots, the LFTA showed a peak force (59 N to 69 N) during maximum plantarflexion in the final moment of the lift off. During landing, the force developed by the LFTA reached its peak value (61 N to 70 N) at the first contact with the floor. After that, the LFTP developed a peak force (70 N to 118 N). This model allows the calculation of forces in lateral ankle ligaments. The information obtained in this study can serve as a basis for future research on ankle sprain and ankle sprain simulation.

1. Introduction

Handball is one of the top four athletic games with highest injury risks (Luck and Glende, 1996). The jump shot is the most accomplished goal shot technique during which ankle injuries are a common occurrence (Whiting and Zernicke, 2008).

Models can be very useful to investigate lesions of the musculoskeletal system. However, the "Full-Body Model" (Version 2.3, MusculoGraphics Inc., Chicago, IL, USA) is still not complete to simulate ankle injuries.

The ankle joint complex (AJC) is generally differentiated between the talocrural joint (TCJ) and the subtalar joint (STJ). The TCJ has a large component of rotary motion around this axis known as plantarflexion and dorsiflexion (Tuijthof et al., 2009). The STJ is considered to be one functional unit of multiple segments (articulatio subtalaris, articulatio talocalcaneonavicularis), allowing a rotary motion around this axis known as inversion and eversion. At the subtalar joint, inversion is coupled with plantarflexion, adduction and supination, and eversion is coupled with dorsiflexion, abduction and pronation (Kleipool and Blankevoort, 2010).

Ligamentous injury is commonly reported due to inversion strains (Morrison and Kaminski, 2007). The anterior talofibular ligament is one of the most exclusively injured structures overall in the human body (Steinbrueck, 1996). To provide a basis for injury simulation, the objective of this study is to calculate and visualise ligament force scenarios during the jumping and landing phases of controlled jump shots.

Table 1
List of recorded motions, duration of contact to ground (s), mean marker error and the corresponding standard deviation (mm) of the jumping/landing leg for the inverse kinematics.

Recorded motion	Duration of contact to ground (s)	Mean marker error (mm)
Jump 1	0.225	12 ± 5
Jump 2	0.192	12 ± 4
Jump 3	0.183	12 ± 5
Landing 1	0.241	16 ± 7
Landing 2	0.200	15 ± 7
Landing 3	0.317	14 ± 8

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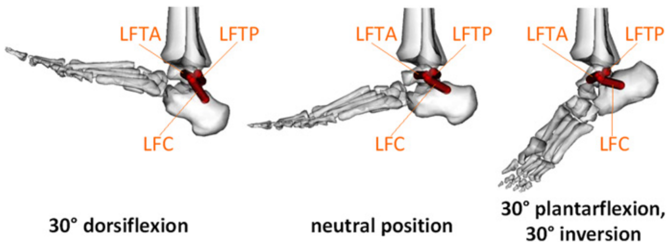

Fig. 1. Illustration of the ankle including three modelled lateral ankle ligaments. (LFTA lig. fibulotalare anterius, LFTP lig. fibulotalare posterius, LFC lig. fibulocalcaneare).

2. Materials and methods

2.1. Data collection

One handball player (youth national team of Austria, age 17 years, height 1.80 m, body mass 86 kg) performed six habitual left-legged jump shots to attempt simulated shots. An extended Helen Hayes marker set (Richards, 2008) with 42 reflecting markers were positioned on the player. Ten cameras (Eagle Digital, Motion Analysis Corp., Santa Rosa, CA, USA) at a sample-frequency of 120 Hz recorded three takeoffs and three landings (Table 1) with Cortex (1.3.0.475, Motion Analysis Corp., Santa Rosa, CA, USA). A force plate (Kistler Instrumente AG, Winterthur, Switzerland) was used to measure the ground reaction forces and torques.

Table 2
List of implemented lateral ankle ligaments, Breaking load (N) of ligaments (Alt, 2001), joint position (degrees) for the transition between slack and taut (Taser et al., 2006), calculated peak isometric force (N), tendon slack length (mm) and tendon slack length after the scaling process (mm).

Ligament	Breaking load (N)	Joint position at slack-taut transition (degrees)	Peak isometric force (N)	Tendon slack length (m)	Tendon slack length after scaling process (m)
LFTA	177	16° PF	32.4	19.6	21.9
LFTP	260	17° DF	30.4	21.5	24.1
LFC	316	18° DF	44.9	27.9	31.3

LFTA lig. fibulotalare anterius, LFTP lig. fibulotalare posterius, LFC lig. fibulocalcaneare, PF plantarflexion, DF dorsiflexion.

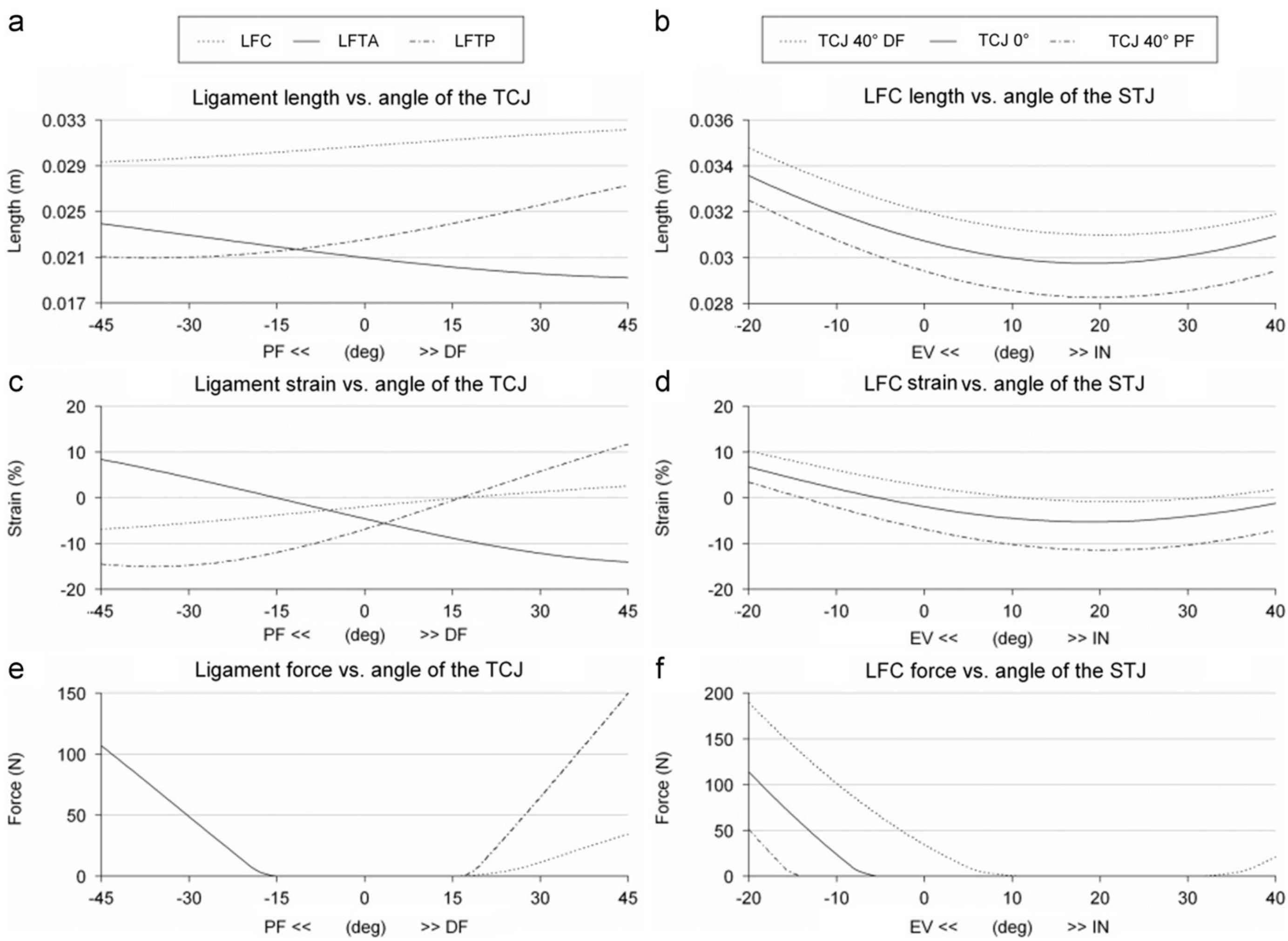

Fig. 2. Overview of the properties of the implemented ligaments. Figures are showing the ligament length (a), strain (c) and force (e) versus TCJ motion. The LFC length (b), strain (d) and force (f), with different angles in the TCJ, versus STJ motion are represented. (TCJ talocrural joint, STJ subtalar joint, LFC lig. fibulocalcaneare, LFTA lig. fibulotalare anterius, LFTP lig. fibulotalare posterius, PF plantarflexion, DF dorsiflexion, EV eversion, IN inversion).

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2.2. Modelling ligaments

The generic "Full-Body Model" based on SIMM (5.0, MusculoGraphics Inc., Chicago, IL, USA) (Delp and Loan, 2000, 1995) was reduced to 43 degrees of freedom. The AJC was defined by two joints in the existing model as an approximated reduction. Both joints had one degree of freedom, these being plantarflexion/dorsiflexion in the TCJ and inversion/eversion in the STJ (Delp et al., 1990).

The added lateral ankle ligaments (Fig. 1): ligamentum fibulotalare anterius (LFTA), ligamentum fibulotalare posterius (LFTP) and ligamentum fibulocalcaneare (LFC) were modelled using the muscle editor in SIMM. The origin and insertion of the ligaments, corresponding to bony structures and their orientation in space, were derived from publications (Golanó et al., 2010; Kleipool and Blankevoort, 2010; Valderrabano et al., 2009). Each ligaments' tendon slack length setting was based on the slack-taut transition according to Kleipool and Blankevoort (2010) (Table 2). Ligaments were modelled acting like so called "passive muscles", which means the fibres of zero length. Thus the force-length curves were exclusively used to calculate the ligaments' force without active force properties. The progression of the force-length curve of each ligament was designed to match the critical breaking load at 20° overstraining in the joint (Alt, 2001) (Table 2). For the LFC, the STJ was additionally set to 10° more eversion than the model's maximum range of motion.

2.3. Inverse dynamics with OpenSim

The model was scaled with a uniform scaling method (similar to Saraswat et al., 2010) in OpenSim 2.2.0 (Simbios, Stanford University, CA, USA) (Delp et al., 2007). The marker adjustment and inverse kinematics tool processed the recorded data to analyse the model's optimal position for each frame by varying the joint angles during the "weighted least squares error calculation" for each marker (Delp et al., 2007). The inverse dynamics tool, including applied ground reaction forces, was additionally used to calculate the progression of the forces for each implemented ligament.

3. Results

3.1. Modelled ligaments

The LFTA and the LFTP/LFC were working contrariwise. The LFTP and the LFC elongated from the neutral position of the TCJ to dorsiflexion. The LFTA elongated from dorsiflexion to plantarflexion

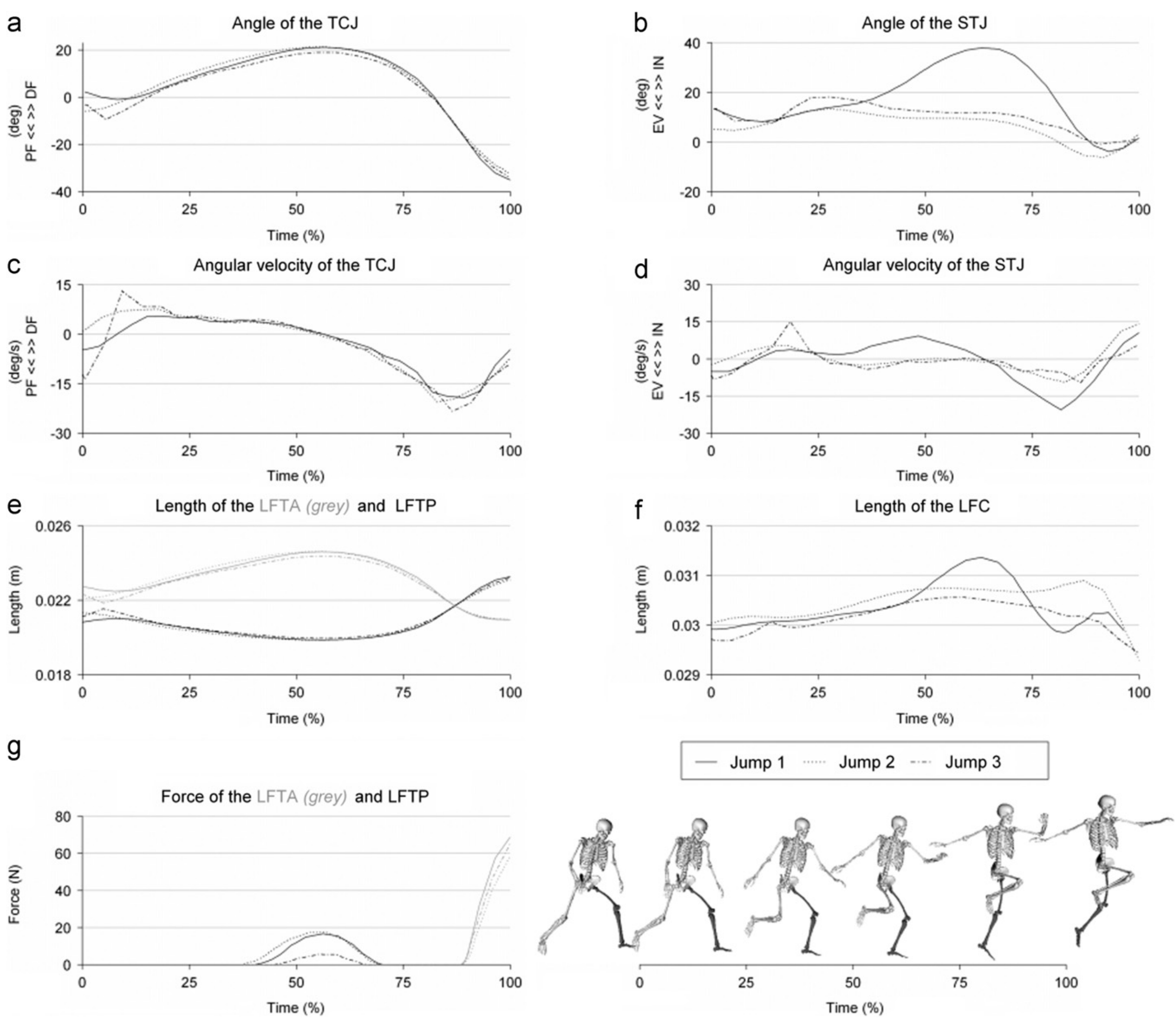

Fig. 3. Ankle and lateral ligament processes of the jumping leg. The figures are showing the angularity of the TCJ and STJ (a, b), the angular velocity of the TCJ and STJ (c, d), the ligament length (e, f) and the ligament force (g) of the (left) jumping leg. The timelines represent the duration from initial to final ground contact. (TCJ talocrural joint, STJ subtalar joint, PF plantarflexion, DF dorsiflexion, IN Inversion, EV Eversion, LFTA lig. fibulotalare anterius, LFTP lig. fibulotalare posterius, LFC lig. fibulocalcaneare).

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(Fig. 2a). The LFC shortened from maximum eversion to a minimum length at +18.8° inversion (Fig. 2b).

Highest strains were observed for the LFTA (8.4%) at maximal plantarflexion and for the LFTP (11.7%) at maximum dorsiflexion. The largest strain for the LFC (10.3%) was found at maximum dorsiflexion combined with maximum eversion (Fig. 2d).

Peak force of the LFTA (107 N) was found during maximum plantarflexion, for the LFTP (150 N) during maximum dorsiflexion (Fig. 2e) and for the LFC (35 N) during maximum dorsiflexion. At maximum eversion of the STJ, the peak force of the LFC was 190 N (Fig. 2f).

3.2. Kinematic and dynamic solution

The TCJ was continuously dorsiflexed until a maximum angle (19.0° to 21.3°) was reached at 56% of time (Fig. 3a). The highest mean angular velocities (−19.2°/s to −23.4°/s) occurred during push-off at 86% of time (Fig. 3c). Maximum eversion of the STJ (−0.8° to −6.1°) was found at 92% of time (Fig. 3b). Jump 1 exclusively showed a peak inversion angle (+37.9°) after 63% of the total time duration (Fig. 3b). The peak plantarflexion during lift-off (−35.1° to −32.5°) was observed (Fig. 3a). Peak force of the LFTP (6 N to 17 N) was observed during maximum dorsiflexion (Fig. 3g). The LFTA showed a mean peak force (59 N to 69 N) during maximum plantarflexion. A marginal force of the LFC (<1 N) was exclusively observed within the first jump at the moment of maximum inversion.

At initial floor contact of landing maximum plantarflexion of the TCJ (−33.0° to −35.4°) took place (Fig. 4a). The force developed by the LFTA reached its mean peak value at (61 N to 70 N) in this moment (Fig. 4g). The peak angular velocity of the TCJ (26.4°/s to 27.1°/s) was found at 7% of time (Fig. 4c). The TCJ was continuously dorsiflexed to a peak angle of 30.9° to 39.5° at 63% of time (Fig. 4a). LFTP forces were observed between 70 N and 118 N (Fig. 4g). Dorsiflexion decreased towards lift-off angle (5.1° to 13.9°) (Fig. 4a). Angularities of the STJ ranged from the

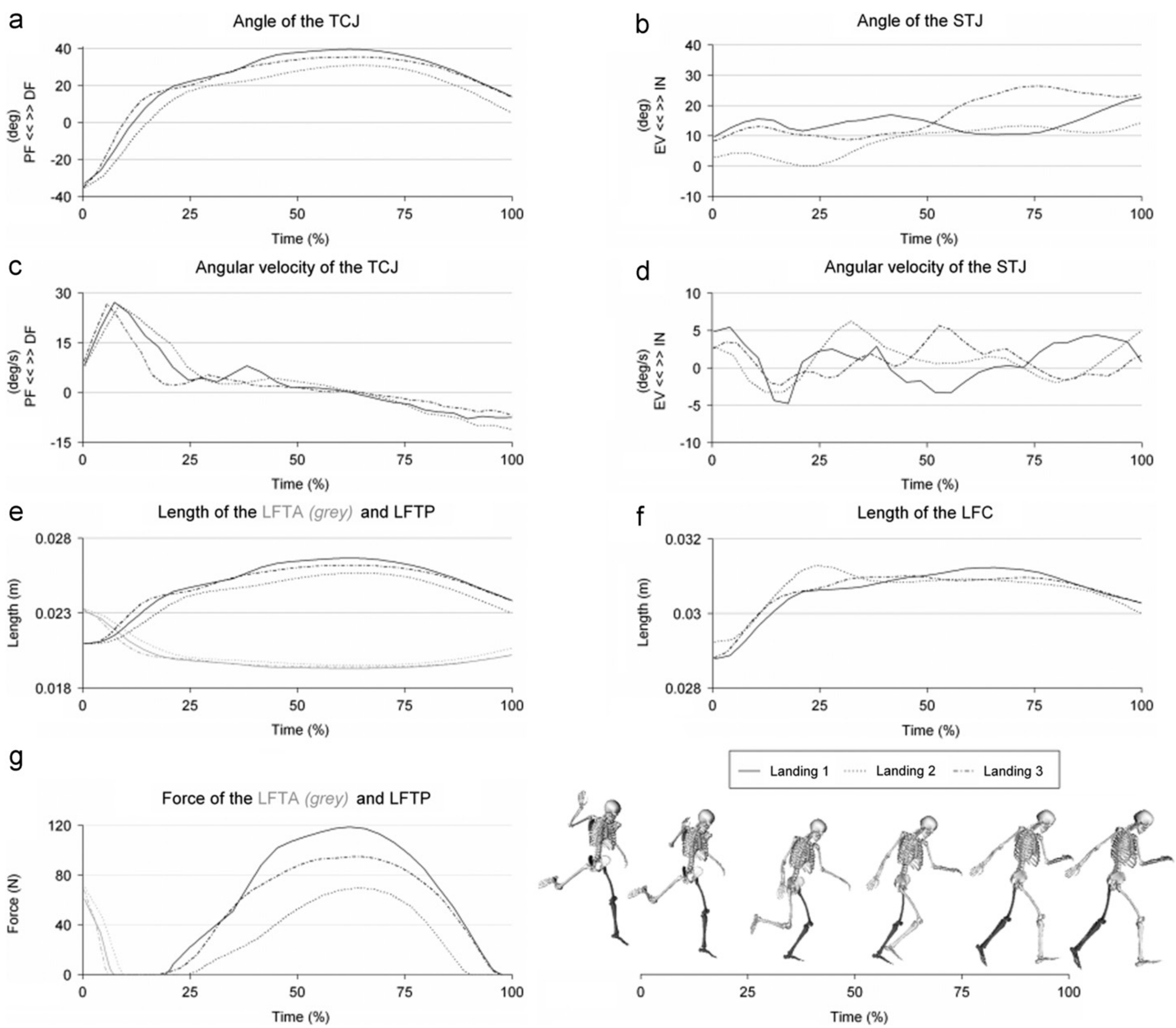

Fig. 4. Ankle and ligament processes of the landing leg. The figures are showing the angularity of the TCJ and STJ (a, b), the angular velocity of the TCJ and STJ (c, d), the ligament length (e, f) and the ligament force (g) of the (left) landing leg. A force for the LFC could not be observed. The timeline represents the duration from initial to final ground contact. (TCJ talocrural joint, STJ subtalar joint, PF plantarflexion, DF dorsiflexion, IN Inversion, EV Eversion, LFTA lig. fibulotalare anterius, LFTP lig. fibulotalare posterius, LFC lig. fibulocalcaneare).

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initial inversion angle (2.9° to 9.7°) to the final inversion angle (14.4° to 23.7°) (Fig. 4b).

4. Discussion

The present study showed the absolute lengths of the modelled ligaments in alignment with reported lengths by Taser et al. (2006) and Ozeki et al. (2002). The LFTA and the LFTP/LFC worked in an opposing state of dorsiflexion and plantarflexion, which is in agreement with other literature (Kleipool and Blankevoort, 2010; De Asla et al., 2009; Bahr et al., 1998; Nigg et al., 1990). The characteristics of the LFC during STJ motion were very sensible to the exact point of insertion: it was located close to an imaginary line, along which the plane, spanned by the axis of rotation of the STJ and the point of origin on the fibula, was piercing through the surface of the calcaneus. The more proximal the insertion was situated to this imaginary line, the more the LFC was strained during inversion and vice versa.

The LFTP had the highest peak strain of all ligaments during ankle motion, matching reported ligament strain calculations by Allard et al. (1985).

Strain of the LFC at 30° dorsiflexion was comparable to the strain reported by Ozeki et al. (2002). Force progression of the model's LFTA was similar to that reported by Bahr et al. (1998). The force developed by the modelled LFC at 11.7° eversion and 15° dorsiflexion lies between the reported forces (Nigg et al., 1990).

The LFTA exclusively developed forces during maximum plantarflexion of jumping and landing. The ligaments loads for the LFTP during dorsiflexion were generally higher for landing than for jumping. The initial contact with the ground during landing occurred with the forefoot in a plantarflexed position. To avoid peaks of load, these characteristics occur with this landing technique, instead of landing with a flat foot (Müller et al., 1992). The moment of initial contact is an unstable condition where a supplementary adduction-inversion-stress could affect the ankle. This risk can be reduced through a less inverted position of the foot in the moment of impact (Müller et al., 1992), because a proprioceptive reaction of compensation during sprain is impossible due to its temporal shortness (Knobloch, 2007).

A model is always restricted and has limitations (Nigg et al., 1990). One limitation of the presented model is scaling of the test person. This includes variation of the anatomy compared to the test person and influences calculation of forces and moments. However the results were in the physiological range (Kleipool and Blankevoort, 2010; De Asla et al., 2009; Bahr et al., 1998; Nigg et al., 1990). In the future individually adapted models are required for more accurate predictions.

The information obtained in this study can also serve as a basis for developing strategies minimising risks of injury, especially in young handball players training and competition. In conclusion, this model allows calculation of lengths and forces of lateral ankle ligaments based on parameters derived from the literature. This study gave a constitutional insight in the force scenarios of lateral ankle ligaments occurring during jump shots.

Conflict of interest statement

None declared.

Acknowledgments

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