THESES OF PHD DISSERTATION

Landing strategy optimization for lower limb injury risk reduction: Combining computational biomechanical modeling and machine learning

Datao Xu

University of Pannonia

Doctoral School of Chemical Engineering and Material Sciences

Veszprém

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Introduction

Landing is one of many fundamental sports techniques, that can commonly be associated or accompanied by sports injuries, such as anterior cruciate ligament (ACL) injury, lateral ankle sprain (LAS), etc. Different landing patterns can expose lower limb joints and ligaments to different loading modes. A successful landing is defined as the body being able to cushion the impact load well enough to maintain body balance and avoid injury. In actual motion monitoring, most current studies of ACL forces during landing have been conducted using biomechanical models such as musculoskeletal models and in vivo studies. However, the establishment of such a model usually requires a large and complex base of knowledge, and the simulation calculation process is usually time-consuming and costly. In recent years, an increasing number of studies have favored the use of machine learning methods to model and predict the complex "input-output" relationship, to address the computational difficulty and cost of important variables in biomechanics.

The first research question of this thesis: Previous studies on the impact of fatigue factors on the lower limb biomechanics during landing tasks often only investigated the effect of fatigue factors on ACL injury risk from some indirect indicators, rather than starting from the perspective of the dynamic loading forces within the ACL itself. However, the limitation is that it cannot explore the exact mechanism of the fatigue factor increasing ACL injury risk from the internal force itself. In addition, it is unclear whether changes in the ankle during after-fatigue landing are associated with an increased risk of ACL injury.

The first research objective of this thesis: To accurately calculate ACL internal dynamic load forces by constructing a musculoskeletal modeling. In addition, this study aims to explore whether there are detectable and recognizable differences in ankle joint kinematics, lower limb joint energy dissipation (joint work) and ACL load force between before-fatigue and after-fatigue landing, as well as to explore the possible relationship between them.

The second research question of this thesis: In clinical landing injury screening, clinical experts mainly performed quantitative description and analysis from the perspective of biomechanics. However, traditional approach has the inherent limitation of losing a large amount of effective information when extracting low-dimensional single-time point discrete variables from high-dimensional time-continuous variables. Meanwhile, the landing patterns are different in the situation of different injury conditions, different control/intervention conditions, and whether there is lower limb injury, which will cause great difficulties for clinical experts in clinical diagnosis. In recent years, the relevant application of explainable machine learning (XML) in clinical diagnosis has increased the trust of experts in this field in the traceability of ML methods, and has been accepted by more and more researchers.

The second research objective of this thesis: To investigate whether XML can help with landing pattern recognition and to what extent it can aid in the interpretation of prediction results. This work firstly compared the classification recognition performances of several classical classification models on two class landing tasks, and then constructed the XML model based on the neural network model with the best recognition performance combined with LRP to explain the model classification recognition results. The current study proposed two approaches to assess the computed interpretability results: 1) assessment from a statistical perspective; and 2) assessment from a clinical perspective. For statistical evaluation, a Statistical Parametric Mapping (SPM) technology based on random field theory was used to detect statistical differences in the input signals, and then to verify whether interpretability results are reasonable based on statistical differences. For clinical evaluation, interpretable results were analyzed clinically by experienced experts in the field to assess their compatibility with clinical features.

The third research question of this thesis: During landing, the knee has the highest risk of injury, and the most common is the non-contact ACL injury, with more than 80% of its injuries occurring during landing tasks. It is also true that ankle sprains, on the other hand, are one of the most common injuries associated with landing, and more than 80% of ankle sprains occur in the lateral. At present, whether ankle joint motion patterns (AICA, AROM) during landing affect joint energy dissipation and the degree of shock load cushioning across the lower limb, or even if there is some association with lower limb injury, remains to be further explored. In assessing the ACL injury mechanism, traditional models mainly set ligaments as having linear force-length characteristics and consider them independent of strain rate.

The third research objective of this thesis: To more realistically revert and simulate the ACL injury mechanics, this study developed a knee musculoskeletal model that reverts the ACL ligament to a nonlinear short-term viscoelastic mechanical mechanism (strain rate-dependent) generated by the dense connective tissue (DCT) as a function of strain. This work was specified: (1) The peak vertical ground reaction force (PVGRF), total energy dissipation (TED), peak ankle sagittal moment, peak knee sagittal moment, and peak hip sagittal moment were used to assess the overall injury risk of the lower limb, and explored their relationships with AICA, AROM. (2) The peak ankle inversion angle (PAIA), and peak ankle inversion moment (PAIM) was used to assess the LAS risk, and hypothesized the positive correlation between them and AICA, AROM. (3)

The ACL model was developed and constructed to calculate ACL dynamic loading forces, and then the PAF was used to assess the ACL injury risk, and hypothesized the negative correlation between them and AICA, AROM. (4) The feasible ankle motion patterns were explored to balance the LAS and ACL injury risk based on the interaction between PAIA and PAF.

The fourth research question of this thesis: During landing, the knee, which serves as the pivotal joint connecting the ankle and hip, is the most susceptible to damage. When the biomechanical mechanisms of internal loads on the human body are explored in the context of the complex external mechanical environment, the current solutions in the field are mainly achieved by finite element analysis (FEA) techniques and musculoskeletal modeling simulations. Previous research has demonstrated that increasing the ankle plantarflexion (ankle initial contact angle: AICA) may increase ankle energy dissipation during landing, thereby reducing the landing impact on the other joints. At present, it is unclear whether increasing the ankle plantarflexion angle during landing would change the knee loading mechanism and further affect ACL injury risk.

The fourth research objective of this thesis: To explore the effects of different ankle plantarflexion angles during SL on knee impact loading and ACL injury risk. The biomechanical properties of the knee joint were planned to be quantified based on musculoskeletal modeling and finite element analysis (foot-ankle-knee integration model). This study employed a joint impact force to evaluate the impact loads on the knee at various landing angles, and calculated the joint negative work to assess the ability of the knee to dissipate the energy impact. Additionally, the ACL internal load forces (musculoskeletal modeling) and ACL stress (finite element analysis) were simulated and calculated to evaluate the ACL injury risk. Meanwhile, landing optimization strategies are further proposed to reduce knee-related injuries based on the possible findings.

The fifth research question of this thesis: In actual motion monitoring, most current studies of ACL forces during landing have been conducted using biomechanical models such as musculoskeletal models and in vivo studies. However, the establishment of such a model usually requires a large and complex base of knowledge, and the simulation calculation process is usually time-consuming and costly. In recent years, an increasing number of studies have favored the use of machine learning methods to model and predict the complex "input-output" relationship, to address the computational difficulty and cost of important variables in biomechanics.

The fifth research objective of this thesis: To develop a highly accurate and easy-to-implement ACL dynamic load force prediction model, which has low input variable demands (sagittal joint angles), excellent generalization capabilities and superior performance in terms of high accuracy. This study first combines long short-term memory (LSTM) algorithm to construct the prediction model, and then introduces a metaheuristic optimization algorithm (SSA) to optimize the prediction model based on existing machine learning models, and further optimizes the prediction results by combining the discovered linear relationship between AICA, AROM and PAF to achieve accurate prediction of the ACL dynamic load force during SL using simple and easy-to-measure kinematic data.

The sixth research question of this thesis: Previous studies in estimating continuous kinematic variables have usually calculated the informative features of a single group from the surface electromyography (EMG) signals of each muscle, and used them as regular features in that motion pattern. However, the features extracted from a single surface EMG channel are extremely sensitive to noise, amplitude cancellation and electrode shifts, which would increase estimation errors. By revealing the neuromuscular control mechanism behind the motor system, muscle synergy can detect movement intention comprehensively and accurately, and its application is expected to help patients in clinical rehabilitation. Adaptive neuro-fuzzy inference system (ANFIS) has the advantages of optimizing membership functions through independent learning and adjusting fuzzy logic rules to establish output functions that adapt to various rules.

The sixth research objective of this thesis: To develop a movement intention detection technology for estimating each joint continuous kinematic variable based on the lower limb muscle synergy pattern, with a view to developing applications for more efficient exoskeleton-assisted rehabilitation training. More specifically, this study extracted the lower limb muscle synergy patterns of healthy subjects and patients through non-negative matrix factorization (NNMF), and then mapped the lower limb muscle synergy patterns to each joint continuous motion variable using the developed ANFIS non-linear regression model. It is hypothesized that the proposed ANFIS model driven by the NNMF-extracted muscle synergy patterns will be able to accurately and reliably estimate lower limb joint movements, and that the effectiveness will also be radiated to patient subjects.

Thesis points

1st Thesis points:

I explored whether there are recognizable differences in the ankle motion patterns between before-fatigue and after-fatigue SL, and further explore the relationship between AIC, AROM and lower limb energy dissipation and PAF.

As shown in Figure 64, the results suggested that the ACL dynamic load force will increase during after-fatigue SL, which suggested that the lower limb neuromuscular fatigue factor would increase the risk of ACL injury. There was a significant difference in ankle motion patterns between before-fatigue and after-fatigue SL, in which the total recognition accuracy was 71.96% and 66.43% for variables ACI and AROM respectively under three classification recognition algorithms. AICA showed a positive correlation with AED ($R^2 = 0.6455$), KED ($R^2 = 0.3606$) and HED ($R^2 = 0.2189$). Similar results were found for AROM, which also showed positive correlations with AED ($R^2 = 0.5850$), KED ($R^2 = 0.3037$), and HED ($R^2 = 0.1538$).

Therefore, the increased risk of ACL injury during after-fatigue SL is related to the decrease of AICA and AROM, and the relationship between AIC, AROM and PAF is highly negatively correlated, the relationship with TED is highly positively correlated. I concluded that lower limb neuromuscular fatigue increases the ACL dynamic loading force during SL, thereby increasing the risk of ACL injury. This result is associated with a smaller AICA (plantarflexion angle) and AROM movement pattern of the ankle joint during after-fatigue SL. By increasing the AICA and AROM during SL, the energy dissipation of the lower limb joints can be increased and the PAF reduced, thus reducing the impact loads on the lower limb joints and reducing lower limb injuries, including ACL injuries.

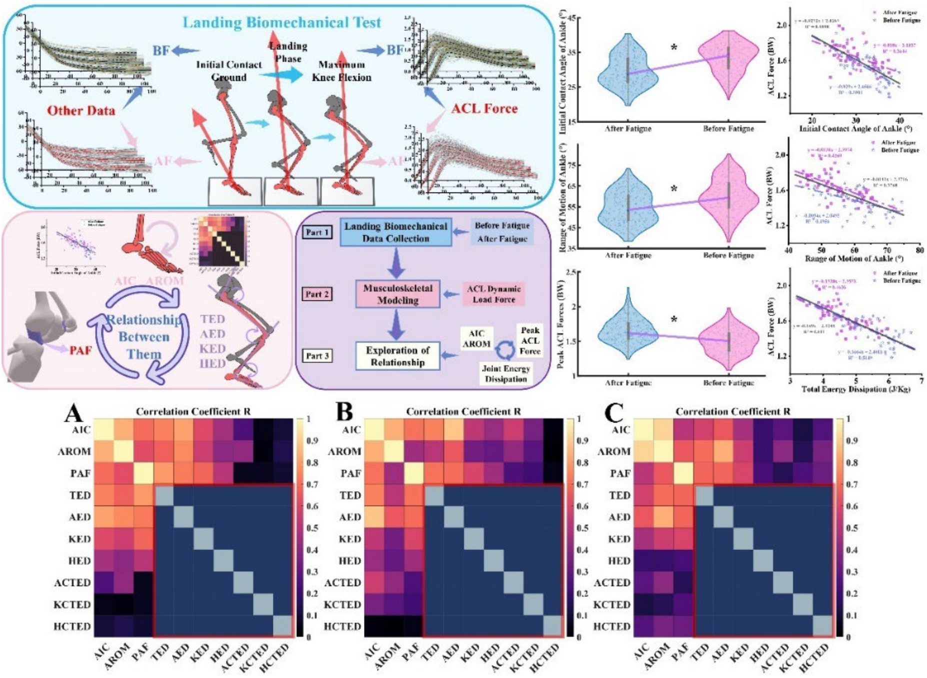

Figure 1 Recognizable differences in the ankle motion patterns and relevant results between before-fatigue and after-fatigue SL.

Related articles to the 1st thesis point:

1. **Xu D**, Zhou H, Quan W, et al. Accurately and effectively predict the ACL force: Utilizing biomechanical landing pattern before and after-fatigue[J]. Computer Methods and Programs in Biomedicine, **2023,** 241: 107761. **Q1, IF=6.1**
2. **Xu D**, Lu J, Baker J S, et al. Temporal kinematic and kinetics differences throughout different landing ways following volleyball spike shots[J]. Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology, 2022, 236(3): 200-208. **Q2, IF=1.1**
3. **Xu D**, Zhou H, Baker J S, et al. An investigation of differences in lower extremity biomechanics during single-leg landing from height using bionic shoes and normal shoes[J]. Frontiers in Bioengineering and Biotechnology, 2021, 9: 679123. **Q1, IF=4.3**
4. **Xu D**, Lu Z, Shen S, et al. The differences in lower extremity joints energy dissipation strategy during landing between athletes with symptomatic patellar tendinopathy (PT) and without patellar tendinopathy (UPT)[J]. Molecular & Cellular Biomechanics, 2021, 18(2): 107. **Q4, EI**

2^{nd} Thesis points:

For the datasets of before-fatigue and after-fatigue landing, I investigated whether XML can help with landing pattern recognition and to what extent it can aid in the interpretation of prediction results. I compared the classification recognition performances of several classical classification models on two class landing tasks, and then constructed the XML model based on the neural network model with the best recognition performance combined with LRP to explain the model classification recognition results (Figure 65).

Meanwhile, the RS results derived from LRP were evaluated from the statistical and clinical perspectives. Both three classification algorithm models achieved high recognizability ($Accuracy > 90\%$) in the nine classification tasks, and the classification performance level of ANN for the input signal is particularly outstanding in comparison to the other two models. From the classification performance, I found that based on the knee data as input signals the classification performance was better ($Accuracy > 95\%$). There is a greater difference in sagittal landing patterns between classes in the three planes.

For the detailed results of RS distribution, I found that the early landing phase contributed more to landing pattern recognition between classes, and the variable contribution during the 1%–22% landing phase reached 27.06%. For each joint, the largest summed contribution rate of RS was 41.02% in the knee joint, followed by 30.62% in the ankle joint and 28.36% in the hip joint. For each plane, the largest summed contribution rate of RS was 37.78% in the sagittal plane, followed by 32.55% in the transversal plane and 29.67% in the frontal plane. The knee flexion-extension angle variable was the most relevant trajectory variable in landing pattern recognition, and the contribution rate of RS reached 8.31%. Secondly, the knee flexion-extension moment, knee internal-external rotation moment, ankle dorsiflexion-plantarflexion moment, ankle internal-external rotation angle, were the followed relevant trajectory variables in landing pattern recognition, and the contribution rate of RS reached 8.03%, 7.86%, 6.58%, 6.13%, respectively. In conclusion, I highlighted the applicability of XML methods that can interpret the results of ML decisions for clinical landing analysis, and their great promise for future application and implementation.

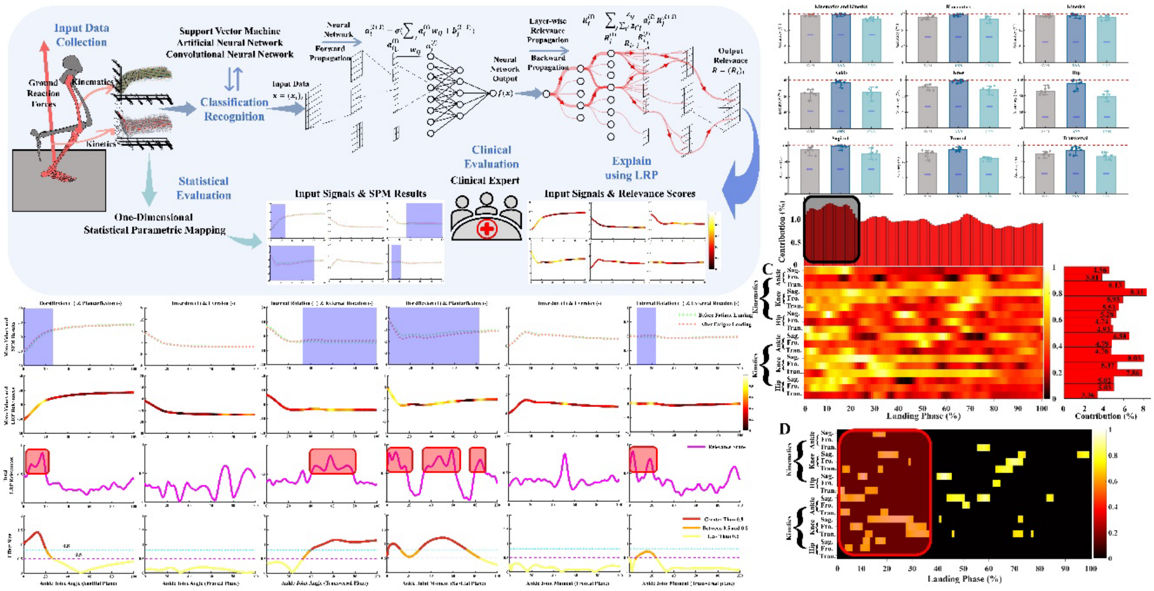

Figure 2 Explainable machine learning models for landing pattern recognition and its results.

Related articles to the 2nd thesis point:

1. **Xu D,** Zhou H, Quan W, et al. A new method applied for explaining the landing patterns: Interpretability analysis of machine learning[J]. Heliyon, **2024. Q1, IF=3.4**
2. **Xu D**, Quan W, Zhou H, et al. Explaining the differences of gait patterns between high and low-mileage runners with machine learning[J]. Scientific reports, **2022**, 12(1): 2981. **Q1, IF=3.8**
3. **Xu D**, Zhou H, Jiang X, et al. New insights for the design of bionic robots: Adaptive motion adjustment strategies during feline landings[J]. Frontiers in Veterinary Science, **2022**, 9: 836043. **Q1, IF=3.2**

3rd Thesis points:

Furthermore, I investigated the relationship between ankle motion patterns (AICA and AROM) and the lower limb injury risk during SL, and proposed an optimized landing strategy that can reduce the injury risk. As shown in Figure 66, to more realistically revert and simulate the ACL injury mechanics, I developed a knee musculoskeletal model that reverts the ACL ligament to a NLSV mechanical mechanism (strain rate-dependent) generated by the DCT as a function of strain.

As shown in Figure 66, the AICA exhibits a negative correlation with PVGRF (r = -0.591) and PAF (r = -0.554), a positive correlation with TED (r = 0.490) and PAIA (r = 0.502). The AROM exhibits a positive correlation with TED (r = 0.687) and PAIA (r = 0.600). The results indicated that the LAS risk is negatively correlated with ACL injury risk (r = -0.330, p < 0.001).

Based on the determined intersection points, I found that 30° to 40° of AICA and 50° to 70° of AROM were the more appropriate range to balance the injury risk between them. This range can be referenced by individuals during SL, but it should also be adjusted according to the person's ankle dorsiflexion ability and the level of muscle function around the ankle joint. In addition, it is also necessary to strengthen the training of the muscles, the medial and lateral tissues, ligaments around the ankle joint, so as to increase the AICA and AROM to reduce lower limb injury risk while avoiding ankle joint injury.

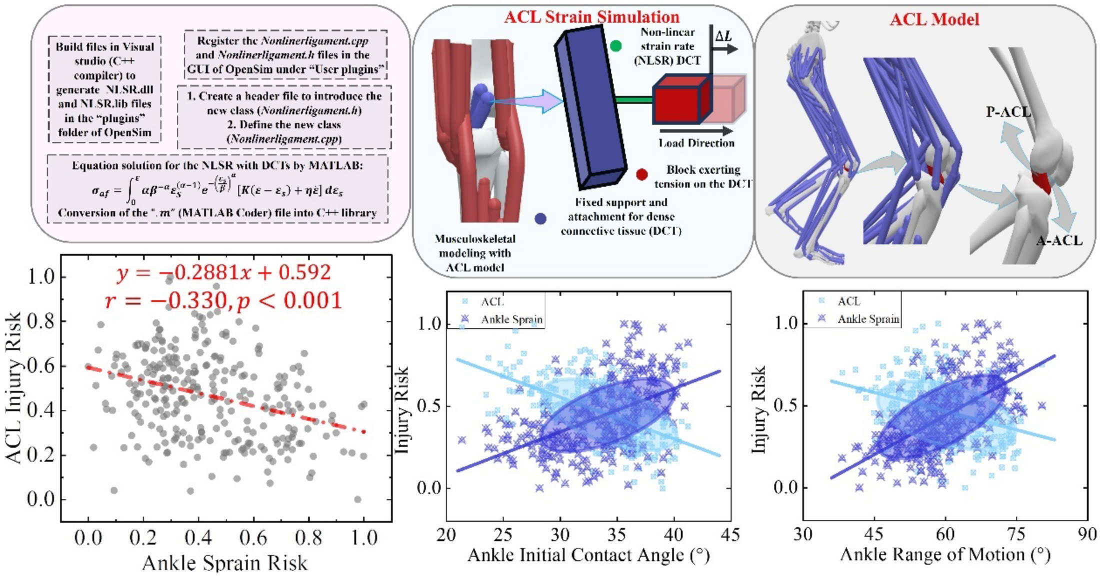

Figure 3 Illustration of the ACL model construction (DCTs with NLSR); Visualization of the interaction between the risk of ACL injury, ankle sprain and AICA, AROM.

Related articles to the 3rd thesis point:

1. **Xu D**, Zhou H, Quan W, et al. New insights optimize landing strategies to reduce lower limb injury risk[J]. Cyborg and Bionic Systems. **2024**, 5: 0126. **Q1, IF=10.5**
2. **Xu D**, Jiang X, Cen X, et al. Single-leg landings following a volleyball spike may increase the risk of anterior cruciate ligament injury more than landing on both-legs[J]. Applied Sciences, 2020, 11(1): 130. **Q1, IF=2.5**
3. **Xu D**, Cen X, Wang M, et al. Temporal kinematic differences between forward and backward jump-landing[J]. International Journal of Environmental Research and Public Health, 2020, 17(18): 6669. **Q1, IF=4.6**

4th Thesis points:

In addition, I explored the effects of different ankle plantarflexion angles during SL on the risk of knee-related injury. This study developed the finite element model of foot-ankle-knee integration and ACL musculoskeletal model with NLSV mechanical mechanism. The internal load forces (musculoskeletal modeling) and stress (finite element analysis) around the knee joint were simulated and calculated to evaluate the risk of knee-related injury during SL.

As the ankle plantarflexion angle increased during landing, both the peak knee vertical impact force (p=0.001) and ACL force (p=0.001) decreased significantly (Figure 67). The maximum von Mises stress of ACL, meniscus, and femoral cartilage decreased as the ankle plantarflexion angle increased. When landing at 20°, 30°, and 40°, the maximum ACL stresses were 30.856 MPa, 27.053 MPa, and 24.592 MPa; the maximum meniscus stresses were 22.315 MPa, 20.073 MPa, and 17.972 MPa; and the maximum femoral cartilage stresses were 18.754 MPa, 17.012 MPa, and 15.429 MPa, respectively (Figure 67).

The overall range of variation in ACL stress was small and was mainly distributed in the femoral and tibial attachment regions, as well as in the mid-lateral region. The current findings revealed that the use of larger ankle plantarflexion angles during landing may be an effective solution to reduce knee impact load and the risk of rupture of the medial femoral attachment area in the ACL.

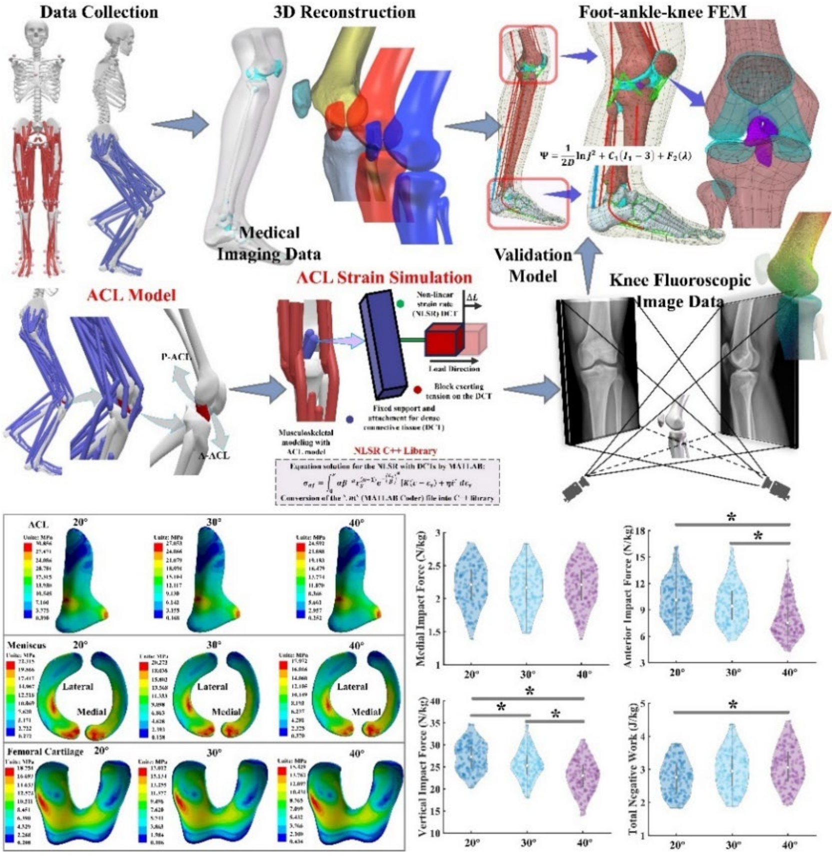

Figure 4 Overview of the model creation and impact load results.

Related articles to the 4^{th} thesis point:

1. **Xu D**, Zhou H,Wang M, et al. Contribution of ankle motion pattern during landing to reduce the knee-related injury risk [J]. Computers in Biology and Medicine, **2024**, 180: 108965. **Q1, IF=7.0**
2. **Xu D**, Zhou H, Zhang Q, et al. A new method proposed to explore the feline's paw bones of contributing most to landing pattern recognition when landed under different constraints[J]. Frontiers in Veterinary Science, **2022**, 9: 1011357. **Q1, IF=3.2**
3. Zhou H, **Xu D,** Quan W, et al. Effects of different contact angles during forefoot running on the stresses of the foot bones: a finite element simulation study[J]. Frontiers in Bioengineering and Biotechnology, **2024,** 12. **Q1, IF=4.3**
4. Zhou H, **Xu D**, Quan W, et al. Can the Entire Function of the Foot Be Concentrated in the Forefoot Area during the Running Stance Phase? A Finite Element Study of Different Shoe Soles[J]. Journal of Human Kinetics, **2023**, 92. **Q1, IF=2.3**
5. Zhou Z, Zhou H, Jie T, **Xu D**, et al. Analysis of Stress Response Distribution in Patients with Lateral Ankle Ligament Injuries: A Study of Neural Control Strategies Utilizing Predictive Computing Models[J]. Frontiers in Physiology, 15: 1438194. **Q2, IF=3.2**

5th Thesis points:

Data-driven machine learning approaches are believed to perform modeling calculations faster than musculoskeletal models and also have higher prediction accuracy. I developed an ACL force prediction model by combining deep learning and the explored relationship between ACL force and ankle motion pattern.

By substituting AICA and AROM as independent variables in the SSA-ELM prediction model (Figure 68), the model shows excellent prediction performance because of very strong correlation ($R^2 = 0.9992, MSE = 0.0023, RMSE = 0.0474$). Based on the equal scaling by combining results of SSA-ELM and SSA-LSTM, the prediction model achieves excellent performance in ACL force prediction of the overall waveform ($R^2 = 0.9947, MSE = 0.0076, RMSE = 0.0873$).

Therefore, my study proposed a method for constructing a highly accurate and easy-to-implement ACL dynamic load force prediction model, which has low input variable demands (sagittal joint angles), excellent generalization capabilities and superior performance in terms of high accuracy.

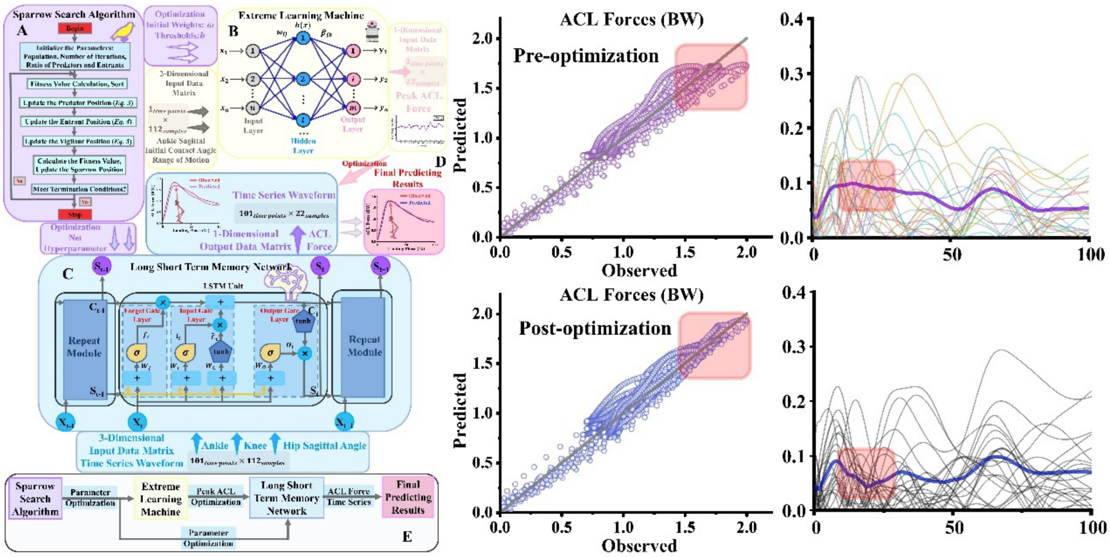

Figure 68 ACL dynamic load force prediction model and its prediction results.

Related articles to the 5th thesis point:

1. **Xu D**, Zhou H, Quan W, et al. Accurately and effectively predict the ACL force: Utilizing biomechanical landing pattern before and after-fatigue[J]. Computer Methods and Programs in Biomedicine, **2023,** 241: 107761. **Q1, IF=6.1**
2. **Xu D**, Zhou H, Quan W, et al. A new method proposed for realizing human gait pattern recognition: inspirations for the application of sports and clinical gait analysis[J]. Gait & Posture, **2024,** 107: 293-305. **Q1, IF=2.2**

6th Thesis points:

To achieve an accurate estimation of lower limb joint movements during landing, I further proposed a novel movement intention detection technology for estimating lower limb joint continuous kinematic variables following muscle synergy patterns, to develop applications for more efficient assisted rehabilitation training. The surface electromyography of 12 muscles and lower limb joint kinematic and kinetic data from healthy subjects and patients during step-off landings from 30 cm-high stair steps were collected. The lower limb neuromuscular synergy pattern was then imported into the developed adaptive neuro-fuzzy inference system non-linear regression model to estimate the human movement intention during this movement pattern (Figure 69).

Six muscle synergies were determined to construct the muscle synergy pattern driven ANFIS model. Three fuzzy rules were determined in most estimation cases. As shown in Figure 69, combining the results of the four error indicators across the estimated variables indicates that the current model has excellent estimated performance in estimating lower limb joint movement. The estimation errors between the healthy (Angle: R^2=0.98±0.03; Torque: R^2=0.96±0.04) and patient (Angle: R^2=0.98±0.02; Torque: R^2=0.96±0.03) groups are consistent.

The proposed model of this study can accurately and reliably estimate lower limb joint movements, and the effectiveness will also be radiated to the patient group. This revealed that the models also have certain advantages in the recognition of motor intentions in patients with relevant movement disorders.

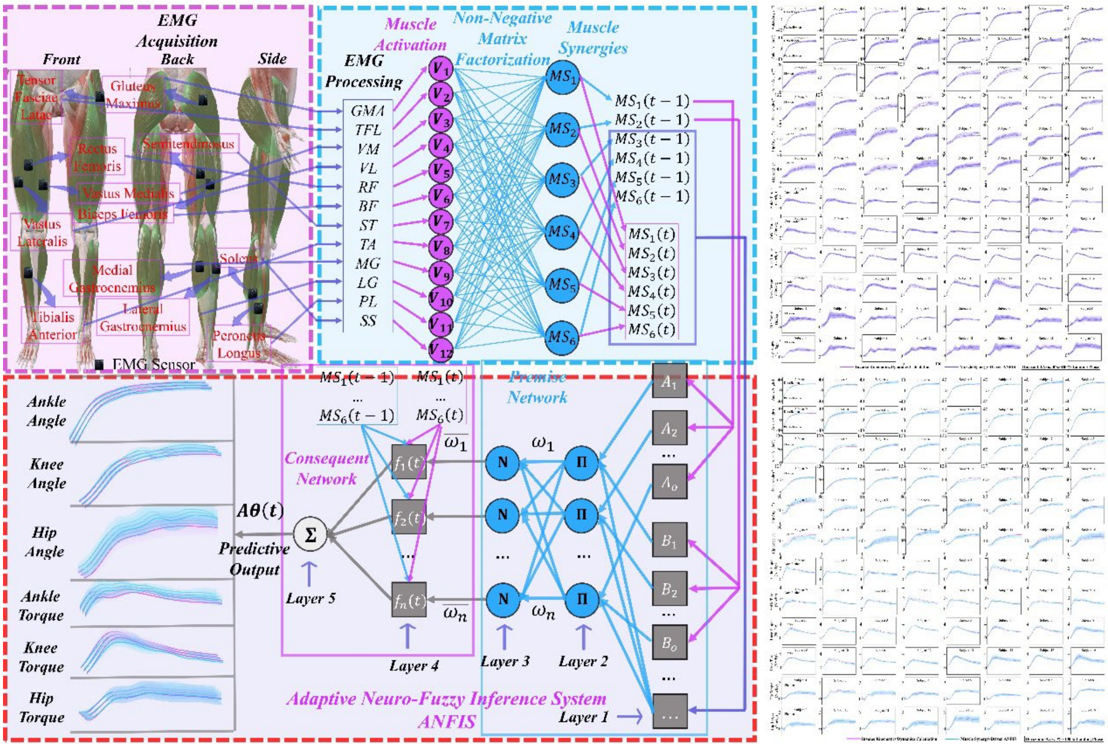

Figure 69 Overview of the NNMF-ANFIS model creation and prediction model results.

Related articles to the 6th thesis point:

1. **Xu D**, Zhou H, Quan W, et al. Adaptive neuro-fuzzy inference system model driven by the non-negative matrix factorization-extracted muscle synergy patterns to estimate lower limb joint movements[J]. Computer Methods and Programs in Biomedicine, **2023,** 242: 107848. **Q1, IF=6.1**
2. Jie T, **Xu D**, Zhang Z, et al. Structural and organizational strategies of locomotor modules during landing in patients with chronic ankle instability[J]. Bioengineering, **2024**, 11(5): 482. **Q2, IF=4.6**
3. Gao X, Jie T, **Xu D**, et al. Adaptive Adjustments in Lower Limb Muscle Coordination during Single-Leg Landing Tasks in Latin Dancers[J]. Biomimetics, 2024, 9(8): 489. **Q1, IF=3.4**

List of publications

Referred articles related to this thesis:

1. **Xu D**, Zhou H, Quan W, et al. New insights optimize landing strategies to reduce lower limb injury risk[J]. Cyborg and Bionic Systems. **2024**, 5: 0126. **Q1, IF=10.5**
2. **Xu D**, Zhou H, Quan W, et al. Accurately and effectively predict the ACL force: Utilizing biomechanical landing pattern before and after-fatigue[J]. Computer Methods and Programs in Biomedicine, **2023,** 241: 107761. **Q1, IF=6.1**
3. **Xu D**, Zhou H,Wang M, et al. Contribution of ankle motion pattern during landing to reduce the knee-related injury risk [J]. Computers in Biology and Medicine, **2024**, 180: 108965. **Q1, IF=7.0**
4. **Xu D**, Zhou H, Quan W, et al. Adaptive neuro-fuzzy inference system model driven by the non-negative matrix factorization-extracted muscle synergy patterns to estimate lower limb joint movements[J]. Computer Methods and Programs in Biomedicine, **2023,** 242: 107848. **Q1, IF=6.1**
5. **Xu D,** Zhou H, Quan W, et al. A new method applied for explaining the landing patterns: Interpretability analysis of machine learning[J]. Heliyon, **2024. Q1, IF=3.4**
6. **Xu D**, Zhou H, Quan W, et al. A new method proposed for realizing human gait pattern recognition: inspirations for the application of sports and clinical gait analysis[J]. Gait & Posture, **2024,** 107: 293-305. **Q1, IF=2.2**
7. **Xu D**, Quan W, Zhou H, et al. Explaining the differences of gait patterns between high and low-mileage runners with machine learning[J]. Scientific reports, **2022**, 12(1): 2981. **Q1, IF=3.8**
8. **Xu D**, Zhou H, Jiang X, et al. New insights for the design of bionic robots: Adaptive motion adjustment strategies during feline landings[J]. Frontiers in Veterinary Science, **2022**, 9: 836043. **Q1, IF=3.2**
9. **Xu D**, Zhou H, Zhang Q, et al. A new method proposed to explore the feline's paw bones of contributing most to landing pattern recognition when landed under different constraints[J]. Frontiers in Veterinary Science, **2022**, 9: 1011357. **Q1, IF=3.2**
10. **Xu D**, Zhou H, Baker J S, et al. An investigation of differences in lower extremity biomechanics during single-leg landing from height using bionic shoes and normal shoes[J]. Frontiers in Bioengineering and Biotechnology, **2021**, 9: 679123. **Q1, IF=4.3**
11. **Xu D**, Lu Z, Shen S, et al. The differences in lower extremity joints energy dissipation strategy during landing between athletes with symptomatic patellar

tendinopathy (PT) and without patellar tendinopathy (UPT)[J]. Molecular & Cellular Biomechanics, **2021**, 18(2): 107. **Q4, EI**

12. **Xu D**, Jiang X, Cen X, et al. Single-leg landings following a volleyball spike may increase the risk of anterior cruciate ligament injury more than landing on both-legs[J]. Applied Sciences, **2020**, 11(1): 130. **Q1, IF=2.5**
13. **Xu D**, Cen X, Wang M, et al. Temporal kinematic differences between forward and backward jump-landing[J]. International Journal of Environmental Research and Public Health, **2020**, 17(18): 6669. **Q1, IF=4.6**
14. **Xu D**, Lu J, Baker J S, et al. Temporal kinematic and kinetics differences throughout different landing ways following volleyball spike shots[J]. Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology, **2022**, 236(3): 200-208. **Q2, IF=1.1**
15. Jie T, **Xu D**, Zhang Z, et al. Structural and organizational strategies of locomotor modules during landing in patients with chronic ankle instability[J]. Bioengineering, **2024**, 11(5): 482. **Q2, IF=4.6**
16. Gao X, **Xu D,** Baker J S, et al. Exploring biomechanical variations in ankle joint injuries among Latin dancers with different stance patterns: utilizing OpenSim musculoskeletal models[J]. Frontiers in Bioengineering and Biotechnology, **2024,** 12: 1359337. **Q1, IF=4.3**
17. Zhou H, **Xu D,** Quan W, et al. Effects of different contact angles during forefoot running on the stresses of the foot bones: a finite element simulation study[J]. Frontiers in Bioengineering and Biotechnology, **2024,** 12. **Q1, IF=4.3**
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19. Gao X, **Xu D**, Li F, et al. Biomechanical Analysis of Latin Dancers' Lower Limb during Normal Walking[J]. Bioengineering, **2023**, 10(10): 1128. **Q2, IF=4.6**
20. Zhou Z, Zhou H, Jie T, **Xu D**, et al. Analysis of Stress Response Distribution in Patients with Lateral Ankle Ligament Injuries: A Study of Neural Control Strategies Utilizing Predictive Computing Models[J]. Frontiers in Physiology, **2024**, 15: 1438194. **Q2, IF=3.2**
21. Zhou Z, **Xu D**, Zhou H, et al. Distinct Motion Control Strategy during Unanticipated Landing: Transitioning from Copers to Chronic Ankle Instability[J]. Journal of Biomimetics, Biomaterials and Biomedical Engineering[J], **2024**, 65: 15-32. **Q4, EI**

22. Gao X, Jie T, **Xu D**, et al. Adaptive Adjustments in Lower Limb Muscle Coordination during Single-Leg Landing Tasks in Latin Dancers[J]. Biomimetics, 2024, 9(8): 489. **Q1, IF=3.4**

International conference abstracts related to this thesis:

1. **Xu D**. NEW INSIGHTS FOR THE DESIGN OF BIONIC ROBOTS. 28th Congress of the European Society of Biomechanics, Maastricht, Netherlands. 2023
2. **Xu D**. Exploring Landing Pattern Differences with Machine Learning-Based Interpretability Analysis. 13th National Sports Science Conference, Tianjing, 2023

International conference full length article related to this thesis:

1. **Xu D**, Zhou H, Gu Y. Relationship between ankle motion pattern and lower limb injury risk during landing. 2023 International Academic Conference on Exercise and Health, Shanghai, China, 2023

Other publications

1. **Xu D**, Song Y, Meng Y, et al. Relationship between firefighter physical fitness and special ability performance: predictive research based on machine learning algorithms[J]. International journal of environmental research and public health, 2020, 17(20): 7689. **Q1, IF=4.6**
2. **Xu D**, Quan W, Zhou H, et al. Exploration of Gait Pattern Differences Between High-Mileage and Low-Mileage Runners Based on Deep Neural Network and Layer-Wise Relevance Propagation. Journal of Medical Biomechanics, **2022. Q4**
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Reviewer for International Journal Articles:

1. Journal of Biomechanics
2. Journal of Sports Sciences
3. Computer Methods and Programs in Biomedicine
4. Computer Methods in Biomechanics and Biomedical Engineering
5. Sports Biomechanics
6. Journal of Bionic Engineering
7. International Journal of Mechanical Sciences

8. iScience
9. Journal of Sports Engineering and Technology
10. Frontiers in Bioengineering and Biotechnology
11. Applied Bionics and Biomechanics
12. Medical & Biological Engineering & Computing
13. BMC Sports Science Medicine and Rehabilitation
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15. Scientific Reports
16. International Journal of Biomedical Engineering and Technology
17. Physical activity and health
18. Frontiers in Physiology
19. Expert Review of Medical Devices
20. Frontiers in Sports and Active Living
21. Physician and Sports Medicine
22. Plos One
23. Bioengineering
24. Molecular & Cellular Biomechanics
25. Applied Science
26. Heliyon
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Guest Editor:

1. Molecular & Cellular Biomechanics
2. Physical activity and health

ORCID: https://orcid.org/0000-0002-1918-0756
Scopus Author ID: 57215841612
Scopus Link:
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