Journal of Trends in Life Sciences
Print ISSN: 2960-0197
Online ISSN: 2960-0200
DOI: https://doi.org/10.61784/jtls3014

STATE EVALUATION MODEL OF MULTIBODY DYNAMIC SYSTEMS: OBJECTIVE RECONSTRUCTION AND COMPUTATIONAL VALIDATION OF FMS FOR THE HUMAN KINETIC CHAIN

RongJin He[1], JunJie Zheng[2], Chen Zhao[3], Rui He[4], WeiBo Shang[4], FangHao Li[5*]
[1]*Super Deer Sport, Xiamen 361000, Fujian, China.*
[2]*Department of Physical Education, Neijiang Normal University, Neijiang 641100, Sichuan, China.*
[3]*Northwestern Polytechnical University, Xi'an 710000, Shaanxi, China.*
[4]*Shanghai Shuangyou Es Sports Culture Development Co., Ltd., Shanghai 200000, China.*
[5]*Faculty of Sport Science and Coaching, Universiti Pendidikan Sultan Idris, Tanjong Malim 35900, Perak, Malaysia.*
[*]*Corresponding Author: FangHao Li*

Abstract: Functional Evaluation of the Human Kinetic Chain is needed in sports biomechanics and rehabilitation. The traditional Functional Movement Screen (FMS) is based on the subject's own observation and only a few scores; therefore, it has poor inter-rater reliability, vague criteria and lacks detailed information. Here is a new computational method proposed in this paper: The "Biomechanical Deviation Scoring Model (BDSM)" is based on the state estimation of multibody dynamic systems, and it is used to convert FMS from a subjective judgment into objective, quantitative calculation of joint kinematic data. The three steps of the model are as follows: (1) Build a template for the joint angle-time trajectory as the "reference system state" (an ideal 3-point movement); (2) Obtain a time series of the joint kinematic states of subjects during standardised movements; (3) Use Dynamic Time Warping (DTW) to find the system deviation between the subject's and the reference trajectories, and then map this deviation to a continuous 0-3 health index using an exponential function. The parameters of the model were obtained from 160 subjects, and 1,000 synthetic trajectories were generated via Monte Carlo simulation for validation. Based on the above results, BDSM values are positively correlated with expert ratings to a certain extent (Spearman's $\rho = 0.89$, $p < .001$). Notably, among the traditional "2-point" category, the BDSM values were 1.32-2.68 (SD = 0.41), and thus a problem in the old system of grouping very different states was exposed. BDSM does not have the problem of discrete scoring boundary effects and offers an objective and reproducible way to construct the evaluation of kinetic chain function.
Keywords: Multibody dynamics; System state estimation; Biomechanical modeling; Dynamic time warping; Kinetic chain functional evaluation

1 INTRODUCTION

Functional assessment of the human kinetic chain system is one of the main problems in the fields of sports biomechanics, rehabilitation engineering and human factors engineering. One of the most common ways to evaluate the functional condition of the kinetic chain in people is the seven-point standardised movement tests of the Functional Movement Screen (FMS): deep squat, hurdle step, inline lunge, shoulder mobility, active straight-leg raise, trunk stability push-up and rotary stability. All of them are individual discrete ordinal scores from 0 to 3, and the sum of these seven scores is called the "composite functional index" of the human kinetic chain system. The predictive validity of the FMS composite score for future injury is not yet known [1].

However, in terms of engineering measurement, there are three basic metrological defects in the FMS scoring system.

First, there is a low-precision measuring tool. The system is based on the subjective judgment of human observers, and without systematic training, the measurement consistency (ICC) among different raters will be low. All measurement systems in engineering that are based on human observation are considered to be low-reliability, qualitative assessment tools.

Ambiguity in the Standards of Measurement. Scoring criteria, such as "trunk is parallel to the tibia", are not quantitative and thus cannot be converted into reproducible physical measurement parameters. It is the same as the uncalibrated scale of a measuring instrument in engineering.

Thirdly, information loss in the low-resolution sensor. Discrete ordinal levels of 0 to 3 quantise the continuously varying biomechanical state signal into four levels and thus violate the basic idea of the Nyquist sampling theorem; the resolution of the measurement system should be high enough to capture the smallest characteristic changes in the measured signal. In addition to the above metrological defects, with the rapid development of FMS, it has also been pointed out that there are characteristics of ritualisation, commodification and pseudoscientific incubation [2]; although it has some clinical value, it also shows that evaluations should be based on measurable and traceable system states. He and others have studied the validity criterion for 76 basketball players and the test-retest reliability of 60 exercisers to

© By the Author(s) 2026, under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0).

obtain new data on the predictive validity and stability of FMS, and also pointed out that discrete composite scores cannot reflect intra-category heterogeneity [3].

To model the motion of a complex system, a person in daily life can be considered a dynamic system composed of several rigid bodies and joints. The Path of this system in configuration space is given by the time series of joint angles. The goal of FMS evaluation is to carry out a "quality assessment" of the output-state trajectory of the system after it has been subjected to some standard inputs; that is, to determine how close the output of the system is to the "reference trajectory" (an ideal 3-point move).

Recently, many databases of human motion states have been released in the field of computational biomechanics. Butler and others (2010) have found that the scores of the various components in the FMS deep squat test are related to all kinds of conditions in the body [4]; subjects who scored 3 points had significantly larger peak hip flexion angles (≥110°), peak knee flexion angles (≥120°) and peak ankle dorsiflexion angles (≥30°) than those who scored 1 point. Based on the above results of system identification, different FMS scores correspond to different regions of the system state and thus have a physical basis for computation. Recently, many more studies have been carried out on measurement technology. Markerless Motion Capture systems (e.g., OpenCap) have been shown to have good agreement with the gold-standard marker-based systems (ICC = 0.89-0.994 and joint angle MAE < 5.2°), and video-based pose estimation algorithms have been added to increase the options for field data collection [5]. The technology mentioned above has increased the collection area of time-series human motion data from laboratories to the field and hospitals. Although some mathematicians have tried to build a mathematical model for the FMS scoring system in previous studies, such as the Compensation-Irritation Matrix (CIM) and the weighted heterogeneous scoring model [6-7], these works are mainly focused on BDSM, and the object of study for BDSM is the deviation of the joint state trajectory rather than item score weights.

Based on the above analysis, this paper introduces a computational model for the state estimation of multibody dynamic systems that has been named the "Biomechanical Deviation Scoring Model (BDSM)". The model for FMS evaluation has been modified to solve the problem of calculating deviation in the system state: (1) A joint angle-time trajectory template for the "reference system state" will be created (this is the kinematic norm of a perfect 3-point movement); (2) Obtain the joint kinematic state vector time series of subjects under standardised exercise conditions; (3) Dynamic Time Warping (DTW) will be used to calculate the system deviation between the subject's state trajectory and the reference trajectory; (4) This deviation will be mapped to a continuous system health index by an exponential state evaluation function.

2 METHODS

2.1 Study Design: System Modelling and Computational Verification

Modelling of Multibody Dynamic Systems and Monte Carlo Simulation are employed in this paper. BDSM is a system of references based on the existing database of human kinematics, and its state-evaluation functions have been computationally verified by simulation. Based on the kinematic data of 160 real subjects, the parameters of the model have been obtained, and multivariate normal sampling is used to generate 1,000 synthetic state trajectories for validation of the statistical properties of the model.

2.2 State-Space Model of the Human Kinetic Chain System

The system of human kinetic chains that can carry out FMS-standardised movements is modelled as an n-degree-of-freedom multi-rigid-body dynamic system. The whole state of the system is given by the joint angle vector $q(t) \in R^n$; here, n is the number of joints considered (this paper focuses on the sagittal plane hip, knee and ankle joints, so n=3).

The motion-state trajectory of the subject in a particular FMS test can be considered a discrete-time series.

$$X=\{x(t_k) \mid k=1,2,\ldots,T\} \quad (1)$$

$x(tk) \in R^n$ is is the state vector of the system (all joint angles) at time tk, and T is the length of the time series.

2.3 Establishment of the Reference System State Trajectory

Reference Trajectory (Golden Template) is the standard joint angle-time series of an ideal 3-point move. According to the biomechanical measurement data in the previous study, the reference-state parameters of the deep-squat test are presented in Table 1.

Table 1 Reference System State Parameters of the Deep Squat Test (3-Point Standard)

System State Variable	Reference Value	Measurement Source
Peak hip flexion angle	≥110°	Butler et al, 2010
Peak knee flexion angle	≥120°	Butler et al, 2010
Peak ankle dorsiflexion angle	≥30°	Butler et al, 2010
Trunk-tibia alignment deviation	<5°	FMS Manual
Knee-foot sagittal deviation	<5°	FMS Manual

At any time, the time-series data of the reference trajectory can be obtained by cubic spline interpolation of a regular movement rhythm (ascending period, steady-state period, descending period).

2.4 Calculation of System State Deviation

Dynamic Time Warping (DTW) is used to compute the system deviation of the subject's state trajectory from the reference trajectory. DTW can also deal with differences in the speed of operation and is thus suitable for the requirement of timescale invariance in the dynamics of multibody systems.
For the subject's state trajectory $X=\{\boldsymbol{x1}, \boldsymbol{x2}, \ldots, \boldsymbol{xTX}\}$ and the reference trajectory $\{\mathbf{y}1, \mathbf{y}2,\ldots,\mathbf{y}TY\}$, an accumulated distance matrix $D \in \mathrm{RTX}\times\mathrm{TY}$ is constructed:

$$D(i,j)=d(x_i,y_j)+\min \begin{cases} D(i-1,j) \\ D(i,j-1) \\ D(i-1,j-1) \end{cases} \tag{2}$$

$d(x_i,y_j) = \|x_i - y_j\|_2$ is the squared Euclidean distance between the system state vectors, that is, the norm of the difference in state vectors in joint-angle space.
The system deviation δ is the normalised DTW distance.

$$\delta = \frac{D(T_X,T_Y)}{T_X \cdot T_Y} \tag{3}$$

The above index has a particular physical meaning; δ is the average Euclidean distance (unit: degrees) of the deviation of the system's state from the reference path per time step, and it accumulates the error in the system output.

2.5 System Health Check Function

The System deviation δ is mapped to a system health score $s \in [0,3]$ by the exponential evaluation function:

$$s(\delta) = 3 * \exp(-\alpha \cdot \delta) \tag{4}$$

Alpha is a small number that sets how sensitive the evaluation function is to changes in the system. The aim of the above function is engineering measurement.

- $\delta = 0 \Rightarrow s=3$; fully in line with the reference state.
- $\delta \to \infty \Rightarrow s \to 0+$ (very far from the reference state)
- Monotonically Decreasing and Continuously Differentiable

The model parameter α is obtained by minimising the mean squared error of the output of the evaluation function and the expert's subjective scores in the expert scoring dataset. This paper takes α=2.5.

2.6 Model Parameter Extraction and Computational Verification

The parameters of the model were obtained from the kinematic data of 160 real subjects, and $\boldsymbol{\mu r} \in \mathrm{R}^3$ and $\Sigma_r \in \mathrm{R}^{3\times3}$ of the system state variables (peak hip, knee, and ankle angles) were obtained for each FMS scoring level (1, 2, 3).

$$\boldsymbol{\mu r} = \frac{1}{N_r} \sum_{i=1}^{Nr} q^{(r)}_i \tag{5}$$

$$\Sigma_r = \frac{1}{N_r - 1} \sum_{i=1}^{Nr} (q^{(r)}_i - \mu_r)(q^{(r)}_i - \mu_r)^\top \tag{6}$$

Let $q^{(r)}_i$ be the state vector of the i-th subject in the r-th scoring category, and Nr be the sample size of this category.
Then, 1000 synthetic state trajectories were obtained by multivariate normal sampling.

$$q^{(r)}_i \sim N(\mu_r, \Sigma_r), i=1,\ldots,N_r \tag{7}$$

The size of each group was set according to the proportion in the original data.

2.7 Evaluation Indicators and Statistical Analysis

The following indices will be used to measure the degree of BDSM.
Spearman's Rank Correlation Coefficient of the Agreement in Rankings Between BDSM Evaluation Values and Expert Subjective Scores.
Inter-group Analysis of Variance: To determine if there are significant differences in the BDSM-evaluation values among the various scores.
Intra-group standard deviation: Find the dispersion of system states in the old discrete scoring categories.

3 RESULTS

3.1 General Distribution of Synthetic State Trajectories

According to the system-state parameters of the 160 real subjects, 1,000 synthetic state trajectories have been generated. Distribution of the score levels in the synthetic data set: 1 point (25.3%, n=253), 2 points (44.2%, n=442) and 3 points (30.5%, n=305); these are in line with the proportions of the original data set.

3.2 Correlation Between Model Evaluation Indicators and Expert Judgments

Spearman's ρ of the correlation between BDSM evaluation values and expert subjective scores was 0.75.

$$\rho = 0.89 \ (p < .001) \tag{8}$$

Therefore, based on the above results, the BDSM model is very close to the traditional expert evaluation method for system state ranking; that is to say, the system states considered superior by experts are also given higher health scores in the BDSM model (Table 2).

Table 2 Group Statistics of BDSM Evaluation Values

Expert Score Level	n	BDSM Mean	BDSM Standard Deviation
3	305	2.71	0.23
2	442	1.97	0.41
1	253	1.04	0.31

One-way ANOVA shows that the means of the three groups in the BDSM evaluation are different (F = 2341.6, p < .001), and all pairwise comparisons according to Tukey's HSD test are significant (p < .001).

3.3 System State Heterogeneity in Traditional Discrete Scoring

The old "2-point" category of BDSM models has shown some diversity in system states. Out of the 442 synthetic samples rated "2 points" by experts, the range of the BDSM evaluation values was 1.32 to 2.68 and the standard deviation was 0.41 (Table 3).

Table 3 Distribution of BDSM Evaluation Values in the "2-Point" Category

BDSM Evaluation Value Range	n	Proportion in the "2-Point" Category
2.50-3.00	37	8.4%
2.00-2.49	162	36.6%
1.50-1.99	165	37.3%
1.00-1.49	78	17.7%

Therefore, the traditional discrete-scoring method has grouped many different parts of the continuous spectrum of system states into one class. 8.4% of the "2-point" samples were actually close to the reference state (3-point region), and 17.7% of the samples were actually closer to the "unable to complete" state (1-point region).

3.4 Increase the Resolution of Measurement

The resolution of the old discrete scoring is 4 in the system's state space. The BDSM model maps the state space of the system to the continuous interval [0, 3] and has a continuous evaluation function; thus, it increases the resolution from 4 levels to about 300 levels (and the scale unit is 0.01) and expands the information capacity by a factor of 75 (Table 4).

Table 4 Comparison of System State Resolution - Discrete Scoring vs. Ongoing Assessment

Evaluation Method	State Space Resolution	Measurement Information Capacity (bits)
Traditional discrete scoring	4 levels	2
BDSM continuous evaluation	>300 levels	>8.2

3.5 Relationship Between System Deviation and Evaluation Value

δ and the BDSM evaluation value are related by the exponential evaluation function s =3*exp(−$\alpha\delta$). When the system deviation increases from 0 to 1.0, the system health score of this function decreases from 3 to about 0.25; thus, it is sensitive to changes in the state of the system.

4 DISCUSSION

4.1 Model Features

According to the BDSM model in this paper, the reconstruction of human kinetic chain functional assessment is a computational problem of system-state deviation. The features of the new model are as follows, and they differ from the old subject-scoring method.

Firstly, Objectivity. Only the evaluation value of BDSM is obtained by analysing the joint angle time series; there are no other subjective judgments from evaluators. Under the same measurement conditions, the difference among repeated measurements is only due to the measurement noise of the motion-capture system (generally less than 3°), and the evaluation value has good repeatability (the theoretical correlation coefficient is close to 1.0).

Secondly, Traceability. All evaluation values in BDSM can be attributed to specific parameters of the system state; that is, the Euclidean distance of the subject's system state from the reference trajectory in three degrees of freedom (hip,

knee and ankle) contributes to the corresponding components of the deviation δ. Therefore, the evaluation results have been given "calibratability" in the sense of an engineering measurement.
Thirdly, continuity. The evaluation values of BDSM are constantly changing in the interval [0, 3], so there is no boundary effect of "dropping a full grade for a minor deficiency" in traditional discrete scoring. Continuous models are very good for quantifying small changes in the state of the evaluation system, such as improvements in the post-rehabilitation training environment.

4.2 Compared with Traditional Ways

The old discrete-scoring method is about to divide the system's state space into four separate regions, and each region will have a relatively large proportion of the state space. Moran and others have systematically investigated and meta-analysed that there is no general association between the FMS composite score and the risk of future injury [1]. Therefore, BDSM should be considered in light of a person's mental health status and not blamed for problems in life. The BDSM model will not lose this information and will continue to track changes in the system. According to the simulation results of this study, the state difference of the system in the traditional "2-point" category (BDSM range 1.32-2.68) covers almost the entire range from the traditional "1 point" to "3 points"; that is, different readings of a measuring instrument have been mistakenly recorded as the same scale value.

4.3 Engineering Feasibility of Measurement Technology

The Engineering Realisation of the BDSM model is based on time-series acquisition of human motion states. With the development of measurement technology, a model for engineering has now been introduced.
Sensor Technology. Markerless Motion Capture Systems (e.g., OpenCap) and Inertial Measurement Units (IMUs) have been shown to be relatively close to the gold standard optical motion capture system Vicon (ICC = 0.89 - 0.994). OpenCap is a markerless system that has been used in the research of lower-limb kinematics [5], and it can also be used as the sensor basis for BDSM applications. The cost of the above-mentioned sensors has fallen from several hundred thousand dollars to a few thousand dollars, and it is still decreasing.
Computation Efficiency. The time complexity of DTW is $O(TX \cdot TY)$, and for typical kinematic series (a sampling rate of 100Hz, movement lasting 2-3 seconds, series length of 200-300 points), the computation time of one evaluation is in the order of milliseconds; thus, it can be used in real time on embedded systems or mobile devices.
System Calibration. Reference Trajectories ("Golden Templates") for the BDSM model need to be divided according to different groups (age, gender, athletic ability), and ranges and reference values should be set for all test subjects in any engineering measurement system.

4.4 Model Limitations and Future Work

Although the BDSM model in this study has achieved some results in kinetic chain analysis, due to the current research environment, the following three problems still need to be solved in the future.
Data Completeness Limitation: At present, the construction of the reference trajectory is based on the complete kinematic data obtained from the deep squat test [4], and the parameters of the reference trajectory for the other six FMS tests have not been systematically obtained through large-sample measurements. In the future, we will add a multi-modal motion capture experiment to increase the size of the benchmark database for all kinds of FMS movements and improve the generalisation evaluation ability of the model.
Lack of kinetic dimensions: The present BDSM model only uses joint angles as the state variables and has not added the necessary kinetic parameters, such as torque and joint power, to fully describe the load of neuromuscular control and characteristics of energy transfer. As per the plan in the research proposal, extend the model to cover the whole state space of multibody dynamics (general position, velocity and torque) and achieve a jump from a purely kinematic description to a coupled evaluation of "kinematics-kinetics".
Experimental verification and system integration extension have not been carried out yet; only the first validation of the model has been done in computational simulation, and its evaluation characteristics in real human kinetic chain systems have not been systematically verified through practical engineering applications. To extend the range of application, continue to observe and record the results of exercise snacks and neuromuscular training for lifelong fitness and fall prevention [8]; BDSM can be used as a kinetic-chain state monitoring unit to customise the optimisation of aerobic exercise based on improved Q-learning and dynamic physiological modelling for chronic disease exercise prescriptions, build a closed-loop control scheme, and have BDSM serve as a sub-module for the kinetic chain state [9]; case studies on different weight-bearing forms for explosive power migration in various sports training have shown that reference trajectories need to be reconstructed according to these different tasks. Clinical translation should determine the limits of medical safety [10], and based on case reports of splenic tuberculosis, motor function assessment cannot be used in place of clinical diagnosis; therefore, unexplained systemic symptoms or pain should first be investigated for other reasons, such as infections [11].

5 CONCLUSION

The above is a computational model to determine the functional condition of the human kinetic chain (BDSM), and it converts the traditional subjective discrete scores into continuous quantitative calculations of system-state deviation for system-state evaluation in multibody dynamics. The following are the main results.
(1) The values of the BDSM evaluation are positively correlated with the expert subjective scores (Spearman's ρ = 0.89, $p < .001$), and thus this computational model can be used in place of the traditional evaluation method.
(2) The range of BDSM evaluation values in the traditional discrete "2-point" category is from 1.32 to 2.68 (SD = 0.41), and it is a significant loss of information that this system-state region is treated as a single category by the old way.
(3) Raise the granularity of the system-state space evaluation from 4 levels to a continuous scale, avoid the boundary effect of discrete scores, and establish a computational platform for precise quantification of functional states in the human kinetic chain.
(4) Given the current low-cost markerless motion capture technology and the improved DTW algorithm, it can be developed and applied.
Next, all FMS test items need to be added to the reference trajectory database, the model should be extended to cover the entire kinetic state space, and finally, the evaluation characteristics of the system will be verified in actual engineering applications of kinetic chain systems.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

ACKNOWLEDGEMENT

We gratefully acknowledge the academic guidance provided by the Chinese TikTok account "Strength and Conditioning Pope".

REFERENCES

[1] Moran R W, Schneiders A G, Mason J, et al. Do Functional Movement Screen (FMS) composite scores predict subsequent injury? a systematic review with meta-analysis. British Journal of Sports Medicine, 2017, 51(23): 1661-1669.
[2] Li F, Huang Y, Zeng Z, et al. Ritual, commodity, and incubator of pseudoscience: a sociological critique on the proliferation of the Functional Movement Screen (FMS). Frontiers in Arts, Humanities & Social Sciences, 2026, 1(3).
[3] He R, Shang W, Li F, et al. FMS predictive validity & stability: criterion (76 basketball athletes) & test-retest (60 exercise participants). World Journal of Sport Research, 2026, 4(2): 13-17.
[4] Butler R J, Plisky P J, Southers C, et al. Biomechanical analysis of the different classifications of the Functional Movement Screen deep squat test. Sports Biomechanics, 2010, 9(4): 270-279.
[5] Turner J A, Chaaban C R, Padua D A. Validation of OpenCap: a low-cost markerless motion capture system for lower-extremity kinematics during return-to-sport tasks. Journal of Biomechanics, 2024, 171: 112200.
[6] Zhao C, He R, Li F, et al. Compensation-irritation matrix (CIM): reconstruction and mathematical and algorithmic validation of the Functional Movement Screen (FMS) scoring system. World Journal of Clinical Sciences, 2026, 4(1): 11-18.
[7] Zheng J, Zhao C, He R, et al. Weighted heterogeneous scoring model: reconstruction and mathematical validation of the Functional Movement Screen scoring system. Journal of Trends in Applied Science and Advanced Technologies, 2026, 3(2): 18-26.
[8] Li F, Li Z, Zeng Z, et al. Redefining lifelong fitness: a practical framework combining exercise snacks and neuromuscular fall prevention strategies. Frontiers in Arts, Humanities & Social Sciences, 2026, 1(3).
[9] Li F, Zeng Z. Personalized optimization of aerobic exercise for type 2 diabetes mellitus patients based on improved Q-learning and dynamic physiological modeling. Fifth International Conference on Information Technology and Contemporary Sports (TCS 2025), SPIE, 2026, 14115: 156-165.
[10] Li F. Comparison of the effects of the different forms of the weight bearing training on the explosive power migration: a case study of Judo. Modern Asia: Politics, Economy, Society, 2026, 1(10): 47.
[11] Liu P, Liu N, Zhang X, et al. Diagnosis and management of splenic tuberculosis: a case report and literature review. Frontiers in Medicine, 2025, 12: 1622794.