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Research Article

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Human elbow joint kinematic model optimization and test based on physiological anatomical analysis

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ABSTRACT

This paper makes analysis to elbow anatomical structural drawings with the examples of elbow joint sports analysis, and establishes proper simple elbow joint sports model through analyzing. Establish elbow joint force analysis model composed from one fixed coordinate and two moving coordinate systems by analyzing anatomical structure image of elbows bones, muscles and joint, and get the formula of three coordinate systems rotation transformation according to relationships between anatomic structure and angle, thereupon set elbow joint sports fitted dynamics equations set on the basis of mechanic analysis as well as give optimized equation solution to definite equations set, finally verify model reliability through actual data. This paper respectively studied physiological anatomic images analysis method and dynamical equations set and optimize method at the same time of exploring elbow joint kinematic features, provide some reference to practices of sports medicine, rehabilitation medicine and clinical medicine.

Key words: Elbow joint, anatomical structure drawing, coordinate transformation, dynamic equation

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INTRODUCTION

Sports analysis is closely related to physiological anatomic, the proper mechanics model can be adopted for research only after getting acknowledge of human joints anatomic image structure. Elbow joint plays an important role in upper limb function, which not only can extend hands activity space but also can drive for hands motion that make movements more stable and accurate. To further research elbow joint motion forms, joint analysis should be done to each elbow part structure status and sports status. This paper is research on elbow joint physiological animatic structure drawings, explore dynamic law that elbow followed in sports process to provide theoretical proof to sports medicine, rehabilitation medicine and clinical medicine [1].

For the analysis of elbow sports status as well as human physiological animatic structure drawings, many scholars have made efforts in succession on it, its research of the two issues propels development of sports medicine, rehabilitation medicine and clinical medicine. If make joint research of the two items can provide a promising start to elbow sports development, some domestic scholars put forward their thoughts and results, among them Song Hongfang [2] establish two rigid systems dynamic model from mechanical dynamic angle through simplify upper limbs structure and use Mathematic software solve the value of model: Hou Xinping [3] To further explore elbow joint biomechanical characteristics, make respective simulation process of human heavy goods lifting, carting and tamping with examples, from which every muscles changing of muscle strength, joint reaction strength and corresponding torque in different speed, flexion and extension angle as well as outside force indicated, get elbow joint sports and joint reaction force changing rules; Luo Bin [4] provide relative data for clinical humerus far end implant design and locate, utilize SPSS software handling structural data of far side 120 sets adults dry humerus, find no significant differences existing in measurements between man and woman, left and right, every items measurements from far side humerus can provide anatomical parameters to design and locate humerus implant [5].

This paper makes analysis of elbow anatomical structure on the basis of previous research, establish joint kinematical dynamic model on the premise that elbow joint structure and elbow joint sports be explored, and make empirical analysis to model to provide theoretical evidence to sports medicine and rehabilitation medicine.

Analysis of human elbow anatomical structure

Elbow joint is the sole joint that human body can achieve both flexion and extension as well as compound movements of medial &lateral rotations, its motion state type as Fig.1 shows, and its different range movements play a very important role in human life. The linkage of elbow joint, shoulder joint and hands plays a role in hands space and sports dynamics extension. Therefore, dynamic analysis of elbow joint can make more accuracy analysis of other human joints sport state. This chapter mainly makes analysis of human elbows bones, muscles and joints anatomical structure so as to provide base to elbow kinematic model through structural analysis.

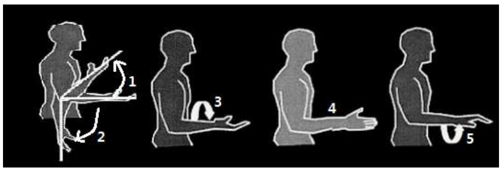

Fig.1: elbow joint motion state schematic diagram

Fig.1 Motion states from 1 to 5 are respectively flexion and extension, stretching, lateral rotation, neutrality and medial rotation.

Analysis of human elbow skeleton anatomical structure: Elbow skeleton has 4 types that is humerus, ulna, radius and radioulna connection, its anatomical structure as Fig.2 shows.

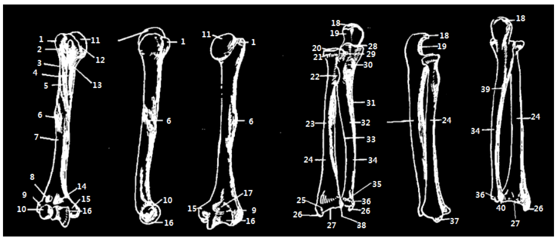

Fig.2: Elbow skeleton anatomical structure diagram

Fig.2: Description from 1 to 40 as Table 1 shows.

Table 1: Table of every part description of Skeleton anatomical structure

No	Name	No	Name	No	Name	No	Name
1	Greater tubercle	11	Head of humerus	21	Articular circumference	31	Inner edge
2	Lesser tubercle	12	Anatomical neck	22	Radial tuberosity	32	Shaft of ulna
3	Crest of the greater tubercle	13	Surgical neck	23	Shaft of radius	33	crest between bones
4	Crest of the lesser tubercle	14	Coronoid fossa	24	radius	34	ulna
5	Intertubercul-ar sulcus	15	Medial epicondyle	25	Radial condyle	35	Articular circumference
6	Deltoid tuberosity	16	trochlea	26	Jugular	36	capitulum of ulna
7	Shaft of humerus	17	Olecranon fossa	27	Carpal articular circumference	37	Jugular
8	Radius fossa	18	olecranon	28	coronoid	38	Incisura ulnaris
9	Lateral epicondyle	19	Inscisura semilunaris	29	radialis	39	Post edge(ulna line)
10	Capitulum of humerus	20	Capitulum of radius	30	Ulnar tuberosity	40	Ulna joint surface

Humerus is the sole bone of human upper arms which is a typical long bone. Such long bone is structurally divided into 3 parts as one unity two ends, superior end and inferior end with body. Hemispheroid in the internal back area of humerus superior end is named as head of humerus that connects to scapula. While the circled slightly narrowed part surround is called anatomical neck, a bulge existing the neck lateral and front areas that are respectively the greater tubercle and lesser tubercle, while the greater tubercle send out a crest backwards that is the crest of greater tubercle; One V-shaped bulged rough surface in the half area of humerus great tubercle crest lateral is the deltoid tuberosity. One spiral typed shallow groove on the back medial of tuberosity is radial sulcus, since musculospiral nerve goes through such groove that easily injured while fraction happened. The smaller tuber located in the front medial area of greater tubercle is the lesser tubercle, under which a down towards long ridges emitted that is the crest of lesser tubercle. A groove locates between greater and lesser tubercle is the intertubercular sulcus. The area that locates joint of humerus superior ends and body is surgical neck; the part is the vulnerable fraction part since it so thin. Humerus inferior expands and its front back sides be flat with condyloid that be higher in lateral, are respectively the medial epicondyle and lateral epicondyle. The back lower area of medial epicondyle is sulcus for ulna, and the trochlea that locates on the medial front between medial and lateral epicondyle is humerus trochlea, a deep fossa on the top of humerus trochlea is the olecranon fossa. The tuber part in the middle of humerus is the shaft of humerus.

Front arm bone is common composed from ulna and radius, from which ulna lies in the medial while radius lies in the lateral, both the two are composed of one unity and two ends. The overall shape of ulna is bigger on top, smaller on bottom, divided into shaft of ulna and upper direction in two ends. Ulna's inferior end gets thin and expands into sphere, its middle part in triangular shape, a forward hook-like prominent on the top of superior end which in semilunar joint surface in front of it.

The shape of radius is smaller on top bigger on bottom, its superior end is the capitulum of radius, the inferior end that gets into flat, widely and swollen condyle is the radial condyle while the middle part is the shaft of radius.

Radius and ulna connect by proximal radioulnar joint, interosseous membrane of forearm and distal radioulnar joint. The proximal radioulnar joint is a part of elbow joint in structure, while make joint movements with distal radioulnar joint on function.

Analysis of human elbow muscle anatomical structure: Human elbow muscle groups can be divided into flexors and extensors on function, among which the flexors mainly including biceps brachii, brachialis, pronator teres, pronator quadratus, the extensors including triceps brachii, anconeus and musculi supinator. Its anatomical structure as Fig.3 shows.

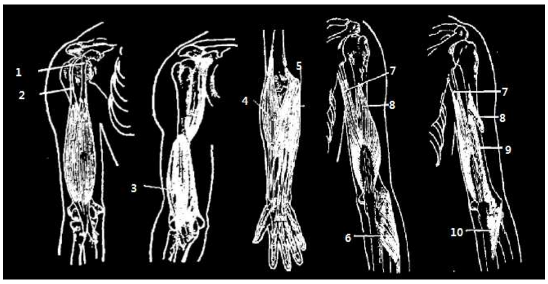

Fig.3: Human elbow muscles anatomical structural drawings

Description from 1 to 10 in Fig.3 as Table 2 shows.

Table 2: Table of each part of human elbow muscle anatomical structure

No.	Name	No.	Name
1	Short head of biceps brachii	6	musculi supinator
2	Long head of biceps brachii	7	long end of triceps brachii
3	brachialis	8	lateral head of triceps brachii
4	brachioradialis	9	Medial head of triceps brahii
5	pronator teres	10	anconeus

Biceps brachii is the strongest muscle in upper arm, that locates on the front superficial layer of upper arm is fusiform muscle with starting point of long end and short end, among which long end starts from scapula tuberosity goes through sulcus, short end starts from sharp area of scapula coracoid, two ends locate on the half front area of humerus and combine into muscle belly, stop at radius tuberosity. Brachialis lies in the front lateral of upper arm, starting from top lateral area of humerus lateral epicondyle; stop at radial condyle's styloid. Pronator teres lies on the top of front medial surface of upper arm, starting from front side of humerus medial epicondyle and ulna olecranon bone surface, stop at middle bone surface of lateral of radius. Pronator quadratus is a deep muscle in square size that lies in the inferior end of region antebrachii volaris, bone sticky surface starting from 1/4 areas under front side of ulna,stopping at 1/4 areas under front side of radius.

Triceps brachii is the strongest muscle on the back of upper arm, its starting point divides into medial head, lateral head and long head, from which medial head starting from the medial side of humerus middle areas, lateral head starting from humerus superior end's lateral area, long head starting from scapula back tuberosity, these three heads lies on the back of humerus combined into muscle belly and form into rectangle aponeurosis. Anconeus is the short bone muscle in the lateral of elbow, lies behind the elbow joint in triangle shape, starting from back under surface of humerus lower ends lateral epicondyle, stopping at 1/4 lateral surface on the superior side of back of ulna. Musculi supinator starts from humerus lateral epicondyle and stops at the front of radius.

Analysis of human elbow joint anatomical structure: The part that connect human forearm bone and upper arm bone is named as elbow joint, its function as enable wrist to fix space and let shoulder joint loads with fore arm. Elbow joint is composed of distal end and radius ulna proximal joint, which is the typical compound joint, its joint capsular thin and loose in front and back side, tense in two sides, joint strengthen is done by ligament. As Fig.4 elbow joint anatomical structure shows.

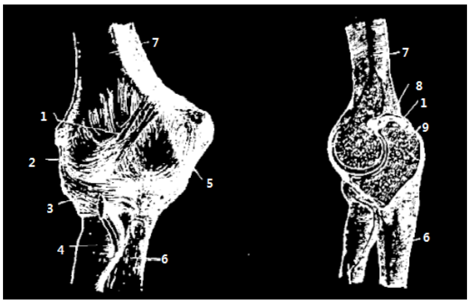

Fig.4: Human elbow anatomical structure drawings

Description from 1 to10 in Fig.4 as Table 3 shows.

Table 3 Table of each parts of Human elbow joint anatomical structure

No.	Name	No.	Name	No.	Name
1	Joint capsular	4	radius	7	humerus
2	Radial collateral ligament	5	ulna collateral ligament	8	horse mouth sized fossa
3	radial ring sized ligament	6	ulna	9	Ulna horse mouth

In elbow stretching process, forearm and upper arm not in the direct line but slightly deviated outside, therefore one angle formed that is carrying angle that should within the range from 7 angles to 13 angles. Humeroulnar joint is the trochlea joint that composed of humerus trochlea and ulna trochlea insicura, mainly responsible for loading between hands and shoulders. Humeroradial joint is the sphere fossa joint that composed of capitulum of humerus and head of radius concaved, since the joint is restricted by ulna that internal adduction and external abduction motion cannot be done. The proximal joint of radius and ulna is the cylinder joint that composed of radial circular joint surface and ulna radialis mainly complete the task of forearm rotation as well as transferring compressed load from hands to upper arm in elbow flexion.

Radial collateral ligament lies in the lateral area of joint capsular, starts from humerus lateral epicondyle, make it into two, surround radial head in front and back directions, stop at the front and back edge of ulna radialis. Ulna collateral ligament lies in the medial of joint capsular, starts from humerus medial epicondyle, its fiber spreading in fan-typed, stop at the front and back edge of notch of ulna trochlea. Radius ring sized ligament is the shape of ring, mainly attached on the front and back edge of notch of ulna radialis with its front and back side together with lateral side surrounding head of radius. Radial collateral ligament and Radius ring sized ligament form the compound radial collateral ligament.

The entire elbow joint cannot resist radius, so ensure medial and lateral rotation motions to radius vertical axis.

Establishment and solution of human elbow joint dynamic model

Elbow joint space simplified structure and coordinate systems defining: Elbow joint simplified schematic diagram as well as coordinate system as Fig.5 shows.

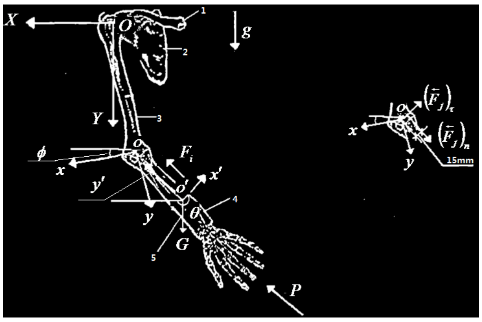

Fig.5: Elbow joint simplified model and its coordinate system schematic diagram

Description from 1to 5 in Fig.5 are respectively clavicle, scapula, humerus, ulna and radius.

As Fig.5 shows, 3 coordinate system of $XOY, xoy, x'o'y'$ have been established with human upper limb anatomical features, from which XOY are fixed coordinate system, unite vector is $(\bar{I}, \bar{J})$ that fixed on shoulder joint, X axis moved from body internal horizontal to external axis vertical back towards, $xoy, x'o'y'$ are moving coordinate system,its unit vector are respectively $(\bar{i}, \bar{j}), (\bar{i}', \bar{j}')$ while fixed on sports body humerus and ulna, y, y' coordinate axis respectively along humerus and fore arm direction directly towards the center of elbow joint, x, x' coordinate axis are respectively vertical to humerus and ulna radius axis line, its pointing status as Fig.5 shows, o, o' are respectively fixed at elbow rotation center and forearm centroid.

Moving coordinate xoy can be described as rotation angle ϕ in y and Y axis to fixed coordinate system, moving coordinate $x'o'y'$ can be described as relative translation component and relative rotation angle θ in X,Y direction from coordinate system's $x'o'y'$ origins to fixed coordinate system, the transformation relationship of 3 coordinate system shown as formula(1).

$$\begin{Bmatrix}\bar{I}\\\bar{J}\end{Bmatrix}=[T_{01}]\begin{Bmatrix}\bar{i}\\\bar{j}\end{Bmatrix}=\begin{bmatrix}\cos\phi & \sin\phi\\-\sin\phi & \cos\phi\end{bmatrix}\begin{Bmatrix}\bar{i}\\\bar{j}\end{Bmatrix},\begin{Bmatrix}\bar{I}\\\bar{J}\end{Bmatrix}=[T_{02}]\begin{Bmatrix}\bar{i}'\\\bar{j}'\end{Bmatrix}=\begin{bmatrix}\cos\theta & -\sin\theta\\\sin\theta & \cos\theta\end{bmatrix}\begin{Bmatrix}\bar{i}'\\\bar{j}'\end{Bmatrix}$$
$$\begin{Bmatrix}\bar{i}\\\bar{j}\end{Bmatrix}=[T_{12}]\begin{Bmatrix}\bar{i}'\\\bar{j}'\end{Bmatrix}=[T_{01}]^T[T_{02}]\begin{Bmatrix}\bar{i}'\\\bar{j}'\end{Bmatrix}=\begin{bmatrix}\cos(\theta+\phi) & -\sin(\theta+\phi)\\\sin(\theta+\phi) & \cos(\theta+\phi)\end{bmatrix}\begin{Bmatrix}\bar{i}'\\\bar{j}'\end{Bmatrix}$$

（1）

In formula（1）$\theta \geq 180^O$， T_i upper corner mark 0,1,2 respectively show as fixed body's scapula, clavicle and moving body's humerus and radial ulna.

Elbow joint sports dynamic equation and equation optimization: Given m as forearm quality，P as external force on elbow joint，G the gravity of forearm，F_i as every muscle force in elbow joint and $i = 1,2,\cdots,6$，$(\bar{F}_j)_\tau, (\bar{F}_j)_n$ respectively show as joint reaction force, τ, n direction are respectively the forearm flexion and extensions tangent and normal direction,，l the length of forearm，l' the distance between forearm centroid and elbow joint rotation center，I_{zz} forearm rotational inertial and $I_{zz} = \frac{1}{3}ml^2$，So that forearm dynamic equation as formula (2)show.

$$\begin{cases} \left(\sum_{i=1}^{6} \bar{F}_i\right)_\tau + \left(\bar{F}_j\right)_\tau + \left(\bar{G}\right)_\tau + \left(\bar{P}\right)_\tau = ml'\ddot{\theta} \\ \left(\sum_{i=1}^{6} \bar{F}_i\right)_n + \left(\bar{F}_j\right)_n + \left(\bar{G}\right)_n + \left(\bar{P}\right)_n = ml\dot{\theta}^2 \\ \sum_{i=1}^{6} M_0\left(\bar{F}_i\right) + M_0\left(\bar{F}_j\right) + M_0\left(\bar{G}\right) + M_0\left(\bar{P}\right) = I_{zz}\ddot{\theta} \end{cases} \tag{2}$$

In formula (2) dynamic equation sets, 6 muscle force and 2 joint reaction force are included. Such 8 items are unknown, equation optimization should be done so as to get elbow motions fixed solution, according to minimum energy consuming principal in human coordination motion, apply minimum muscle stress squares sum as objective function as formula (3) show.

$$J = \min \sum_{i=1}^{6} \left(\frac{F_i}{A_i}\right)^2 \tag{3}$$

In formula (3) A_i as muscle's PCSA value that can be got from table, objective function constraint conditions is the conditions in formula (2) together adding $0 \le F_i \le \sigma \cdot A_i$, σ is muscle stress。

Examples empirical analysis: When elbow suffered vertical and down towards periodical external force, its values of every parameters show as below.

- Elbow joint flexion and extension angular speed $\omega = 0.4$ rad/s;
- Periodic external force $P = 50\sin\left(\frac{\pi}{2}t\right)$;
- Forearm length $l = 27$ cm;
- Forearm quality $m = 1.36$ kg;
- Distance between forearm centroid and elbow joint rotation center $l' = 18$ cm;
- Forearm gravity $G = 13.33$ N;

On the condition of above parameters, objective function in formula (3)'s constraint condition as formula(4) shows.

$$\begin{cases} \left(\sum_{i=1}^{6} \bar{F}_i\right)_\tau + \left(\bar{F}_j\right)_\tau = (13.33 + P)\sin\Psi \\ \left(\sum_{i=1}^{6} \bar{F}_i\right)_n + \left(\bar{F}_j\right)_n = (13.33 + P)\cos\Psi + 0.24\omega^2 \\ \sum_{i=1}^{6} F_i \times r_i + 1.5\left(\bar{F}_j\right)_n = (239.94 + 27P)\sin\Psi, 0 \le F_i \le 100A_i \end{cases} \tag{4}$$

For easy calculation, select starting and ending coordinate of elbow joint 6 kinds of muscles in fixed coordinate system as Table 4 shows.

Table 4: Table of elbow joint 6 kinds of muscles starting and ending pointing coordinate values

Muscles	Starting value(cm)			Ending value(cm)		
	X axis	Y axis	Z axis	X axis	Y axis	Z axis
Biceps brachii	0.0	-1.0	2.5	0.2	36.0	-0.8
Brachialis	0.6	20.0	1.0	-1.2	33.5	0.0
Brachioradialis	-1.5	27.0	0.0	0.0	54.5	0.0
Pronator teres	-3.5	29.0	-0.5	2.0	43.5	0.5
Triceps brachii	1.0	20.0	-0.8	2.0	28.0	-1.5
Anconeus	-2.5	30.0	-1.6	-0.6	30.5	-1.8

Transformation form followed by periodic external force of joint reaction force, muscle force as well as corresponding torque in different ϕ, θ can be got through above data's calculation。From the force image, it can be found that joint reaction force, muscle force as well as corresponding torque's value also show periodicity following by periodic external force. When humerus in the Free State and

$(\phi,\theta)=(0^{O},270^{O}),(10^{O},180^{O}),(10^{O},270^{O}),(10^{O},320^{O}),(20^{O},270^{O}),(30,270^{O})$.

In the half period, elbow reaction force generated from elbow joint all less than 10N,it peak value close to 10N; when $\phi=10^{O},20^{O}$,drag torque change and muscle torque sizes changes base overlapped.

CONCLUSION

This paper studied elbow physiological anatomical structure, respectively make exhibition analysis to elbow bone, elbow muscle and elbow joint anatomic structure drawings, provide space structure base to the establishment of elbow joint dynamic model; The studies follow elbow physiological anatomical structure features, simplify elbow joint force analysis model, and build three coordinate systems in force analysis process, one of which is fixed coordinate system while the other two are moving coordinate systems, get transformation formula of three coordinate system rotation; According to elbow joint outside force status as well as its internal effects correlation, get elbow joint dynamic equation set, and optimize the minimum muscle stress of equation so as to get its solution; Finally, this paper put forward relative testing results, made empirical test on elbow joint sports model, and get proper conclusion, provided theoretical proof to the research of sports medicine, clinical medicine, rehabilitation medicine and biomechanical principal.

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