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Quantification of finger joint loadings using musculoskeletal modelling clarifies mechanical risk factors of hand osteoarthritis

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ABSTRACT

Owing to limited quantitative data related to the loadings (forces and pressures) acting upon finger joints, several clinical observations regarding mechanical risk factors of hand osteoarthritis remain misunderstood. To improve the knowledge of this pathology, the present study used musculoskeletal modelling to quantify the forces and pressures acting upon hand joints during two grasping tasks.

Kinematic and grip force data were recorded during both a pinch and a power grip tasks. Three-dimensional magnetic resonance imaging measurements were conducted to quantify joint contact areas. Using these datasets as input, a musculoskeletal model of the hand and wrist, including twenty-three degrees of freedom and forty-two muscles, has been developed to estimate joint forces and joint pressures.

When compared with the power grip task, the pinch grip task resulted in two to eight times higher joint loadings whereas the grip forces exerted on each finger were twice lower. For both tasks, joint forces and pressures increased along a disto-proximal direction for each finger.

The quantitative dataset provided by the present hand model clarified two clinical observations about osteoarthritis development which were not fully understood, i.e., the strong risk associated to pinch grip tasks and the high frequency of thumb-base osteoarthritis.

1. Introduction

Hand osteoarthritis (OA) is a major public health concern which symptomatic cases were reported for 5–25% of the population [14,26,28,49]. This pathology induces a degeneration of articular cartilage and surrounding tissues [4,26] resulting in loss of grip strength [16,24,29,49], reduced range of motions [25] and other impairments regarding daily tasks [24,29,49]. The treatment of hand OA can vary from conservative methods, e.g., physiotherapy, medication or orthotics, to highly invasive surgery [47]. Understanding risk factors is important to prevent the disease and to improve potential therapies. Genetics, ageing or hormonal issues have been proposed as accounting factors of primary OA (idiopathic cases) [2,22] but no clear evidence has been provided. Conversely, anatomic, metabolic, traumatic and inflammatory disorders have been clearly identified as secondary factors resulting in OA [4]. Especially, the mechanical loadings, i.e., the forces and pressures, acting upon the joints had often been considered as an important risk factor of hand OA because they reflect how the cartilage is used [1,4,21,22,48].

Despite the numerous investigations of the potential risk factors of OA, two aspects of hand OA development remain misunderstood. The first one relates to the risks associated to the grip techniques. Generally, two grip techniques have been compared in the biomechanics literature i.e., the power and the pinch grip. While the power grip almost involves the whole hand palmar surface and is used for forceful tasks (e.g., tool handling or racket sports), the pinch grip is related to fingertips and precision tasks (e.g., writing or sewing) [33]. Intriguingly, several studies have associated OA in the distal interphalangeal (DIP) joints and the pinch grip [20,23,27,32,39], thereby suggesting that this task induces high joint loadings, whereas the grip force measured during this task is around five times lower than the ones reported for the power grip [40]. The second puzzling issue concerns the specific alterations of each finger. OA is indeed more frequent and severe in the most distal joint (DIP) for the long fingers and in the most proximal (trapeziometacarpal, TMC) for the thumb [7,13,49]. Therefore, while the five fingers represent a similar open-chain linkage with 3 mobile segments, they show different adaptations to OA disorders.

Since the two issues presented above relates to mechanical risk factors of hand OA, a quantification of the loadings about finger joints would be helpful. Unfortunately, the assessment of such

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intern variables is very challenging given that their direct in vivo measurements are ethically and technically impossible. Alternatively, musculoskeletal models can provide an estimation of the joint forces using kinematic and external force data as input. Such models have been previously used for either the thumb [10], the index finger [3,9,17,44] or the thumb-index pinch [42] but, for several reasons, the provided estimations are not sufficient to fully comprehend mechanical risk factors of hand OA. First, none of these previous models included all the five fingers and the wrist together and thus neglected the mechanical couplings induced by poly-articular muscles which are important to consider when studying multi-finger tasks [34]. Second, the input data of these previous models were only assumptions rather than experimental in vivo subject-specific measurements. Finally, the joint contact dimensions were not taken into account whereas they represent crucial information to fully describe the risk of damage [32]. One could indeed expect that the risk of damage would be lower if a given force is supported by a large rather than a small contact area.

The objective of the present study was to quantify the forces and pressures acting upon hand joints during two grasping tasks and to interpret this data with regard to the observations concerning mechanical risk factors of hand OA. Considering the two issues described above, we hypothesised that (1) the joint pressure would be higher during the pinch grip than during the power grip for every joint and that (2) the joint pressure would increase along a proximo-distal direction for the long fingers and along a disto-proximal direction for the thumb.

2. Materials and methods

2.1. Experimental set up and grasping protocol

2.1.1. Subjects and protocol

Ten healthy right handed males were recruited for this experiment (age: 25.5 ± 3.2 years; height: 178.6 ± 6.1 cm; weight: 71.2 ± 7.2 kg; hand length: 19.0 ± 0.8 cm; hand width: 8.6 ± 0.5 cm). Each participant was free of upper-right extremity disorder and signed an informed consent. Although hand OA is female predominant [14,24,26,49], the present work focused, as a first step, on analysing how the joint loadings were influenced by different joints or grasping tasks regardless of gender. Furthermore, healthy subjects were chosen, instead of patients, to identify risk factors rather than impairments related to the pathology. The present protocol was approved by the Aix-Marseille University ethics committee.

Each subject was seated and performed two gripping tasks. While the power grip task corresponded to the manipulation of a 3.3-cm diameter cylindrical handle (Fig. 1A), the pinch grip task consisted in grasping a 5.5-cm length sensor between the thumb and index fingertips (Fig. 1B). Participants were asked to seize and raise the object at a comfortable height with their right hand, and then to maximally grasp the object for 6 s. Three exertions were performed for each gripping task and were separated by a 3-min resting period to prevent any effect of fatigue. For each trial, force and kinematic data were simultaneously recorded and synchronised with an external trigger. Only the data corresponding to the trial presenting the highest grip force peak was used for the analysis.

2.1.2. Force analysis for the power grip task

To obtain the distribution of the grip force among hand segments, two measurement systems were combined [19,36]. A cylindrical handle (Handle dynamometer, Sixaxes, Argenteuil, France) split into six beams and instrumented with strain gauges acquired the grip force at 1875 Hz. In addition, the pressure distribution at the hand/handle interface was recorded at 125 Hz using a pressure map (Hoof #3200, TekScan, Boston, USA) which consists in an array of 1089 transducers (33 rows and 33 columns). The pressure map was wrapped around the handle and they were both squeezed during each trial. The six output force signals of the handle were first filtered (Butterworth, 4th order, cut-off frequency: 20 Hz), then re-sampled at 125 Hz. The grip force was computed as the sum of the six filtered signals and averaged over a 750-ms window centred on the force peak. The pressure map data was averaged over the same window and each cell value was expressed as a percentage of the sum of all pressure cell values. A force map, in Newton, was then calculated by allocating the grip force value measured with the 6-beam handle along all the normalised values [19,36]. On this map, specific anatomical areas were identified (Fig. 1D) and each associated with an external force value computed as the sum of the punctual force values in the area. These areas, five per finger, referred to application points which corresponded to either the middle of a segment or a joint rotation centre in the musculoskeletal model [19]. For implementation, each external force obtained from the force map was applied dorsally to each phalanx and onto its associated application point. For the thumb, force directions were orthogonal to the longitudinal axis of the 6-beam handle.

2.1.3. Force analysis for the pinch grip task

The pinch grip object consisted in a customised six-axial force sensor (Nano-25, ATI Industrial Automation, Garner, NC) (Fig. 1B). The six output signals of the sensor corresponded to the three-dimensional (3D) components of the force and the moment applied by the subject. Each output signal was filtered (Butterworth, 4th order, cut-off frequency: 20 Hz), re-sampled at 125 Hz and averaged over a 750-ms window centred on the grip force peak. The three force components were inputted into the musculoskeletal model and applied to the middle of the two distal phalanges.

2.1.4. Kinematic analysis

The 3D position of hand and forearm segments was recorded at 125 Hz using thirty 6-mm diameter spherical reflecting markers (Fig. 1C) and a six-camera optoelectronic system (MX T40, Vicon, Oxford, UK). The marker set consisted in the direct kinematic tracking of dorsal bony landmarks [31]. The first metacarpal and the thumb proximal phalanx were tracked using T-clusters [11]. Three other markers were attached to the grasped objects (Fig. 1A and B). The kinematic analysis was based on the 3D marker positions averaged over the 750-ms window centred on the force peak. Joint angles were calculated from the relative orientation of the distal segment regarding the proximal segment using Euler angles with a flexion/abduction/pronation mobile sequence [3,11]. The local coordinate system associated to each segment was defined from 3D marker positions (Fig. 1C). The coordinate system orientations were such that flexion, abduction and pronation represent positive joint angles.

2.2. MRI measurements

Seven healthy right handed volunteers (age: 23.7 ± 2.7 years; height: 166.6 ± 2.7 cm; weight: 58.9 ± 9.0 kg; hand length: 17.5 ± 0.8 cm) participated to the MRI measurements. The volunteers included four women and three men, two of whom participated in the grasping protocol. Images were acquired with a 3-Tesla MRI scanner (Magnetom Verio, Siemens, Munich, Germany). A small flexible coil was wrapped around the subject's right hand. A platform was adapted to the MRI table to help subjects aligning their hand with the main scanning direction.

Two datasets were collected for each participant: one for the pinch grip and another one for the power grip. In order to prevent any effect of fatigue when participants maintained the posture