A Musculoskeletal Shoulder Model Using Force-Dependent Kinematics to Evaluate Non-Conforming Total Shoulder Arthroplasty

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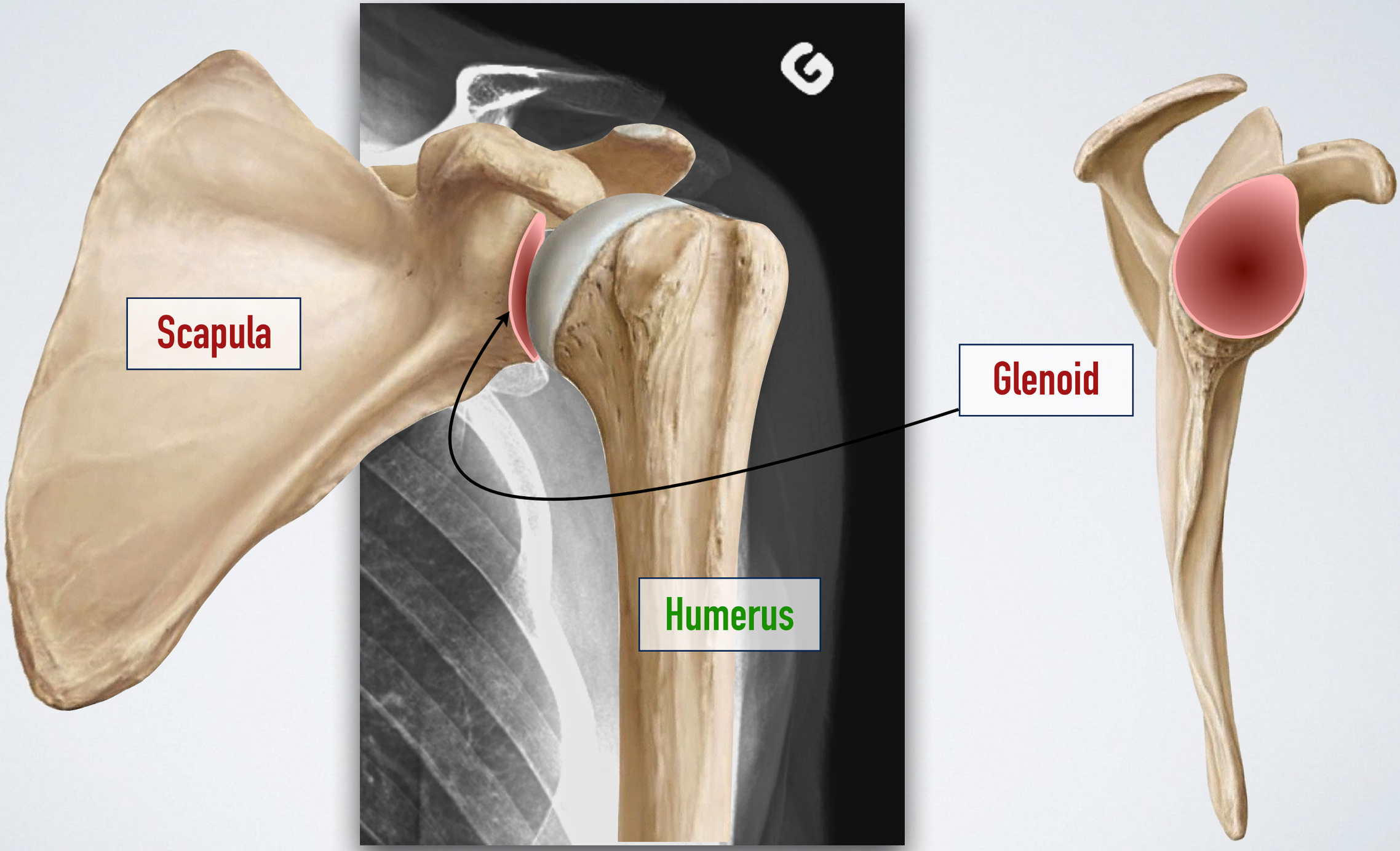
AnyBody Webcast — 04th December 2014

ÉTS Le génie pour l'industrie
CRCHUM CENTRE DE RECHERCHE
Fonds de recherche Nature et technologies Québec

Context

Shoulder: Glenohumeral Joint



Context

Shoulder: Glenohumeral Joint

Healthy shoulder

Pathological Shoulder

- Pain
- Reduced ROM

[1] *Maîtrise Orthopédique n°122 – 03/2013*

Context

Non-Conforming Total Shoulder Arthroplasty

Healthy shoulder

NC-TSA

CONTEXT

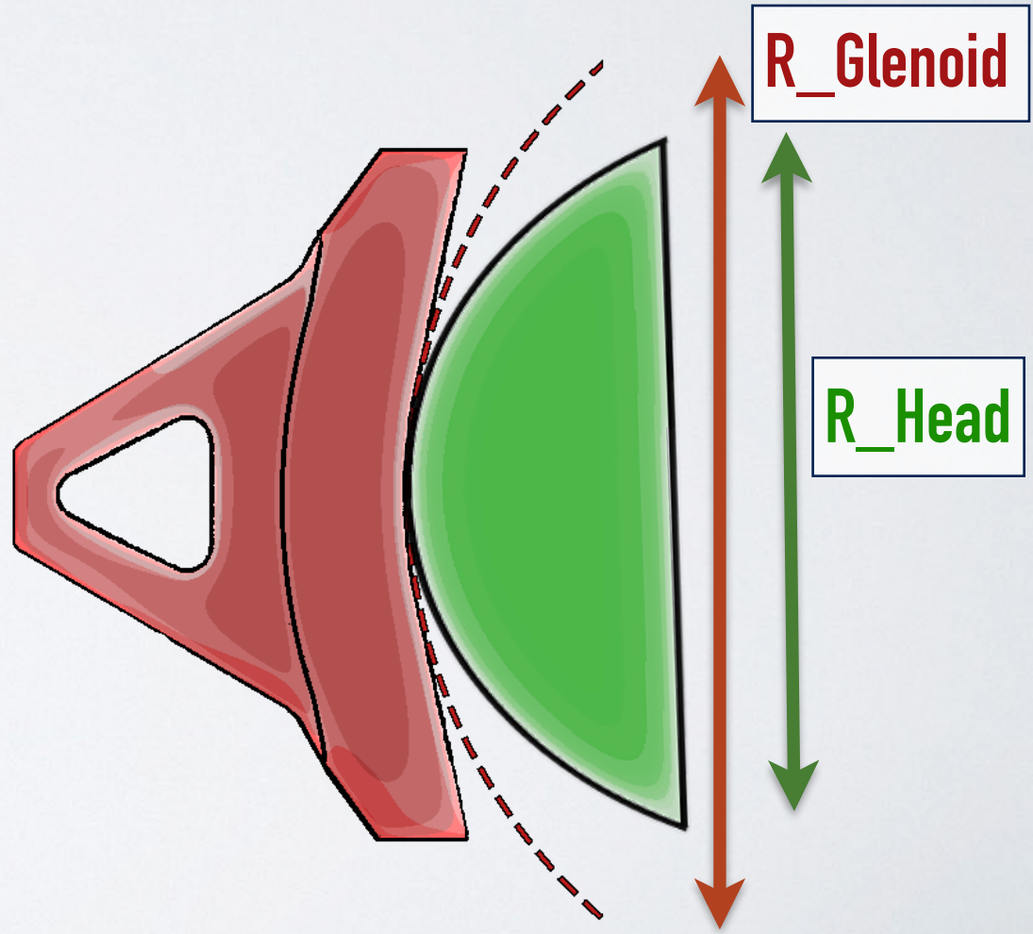
NON-CONFORMING TOTAL SHOULDER ARTHROPLASTY

- **Total:** replacement of the 2 bones of the glenohumeral (GH) joint

- **Anatomic**: reproduction of bones geometry:
  - Prosthetic humeral head (metal) = sphere
  - Glenoid component (plastic) = flat & concave surface

- **Non-conforming**:
  - R_Head < R_Glenoid
  - *Mismatch*

Mismatch = R_Glenoid - R_Head



Context

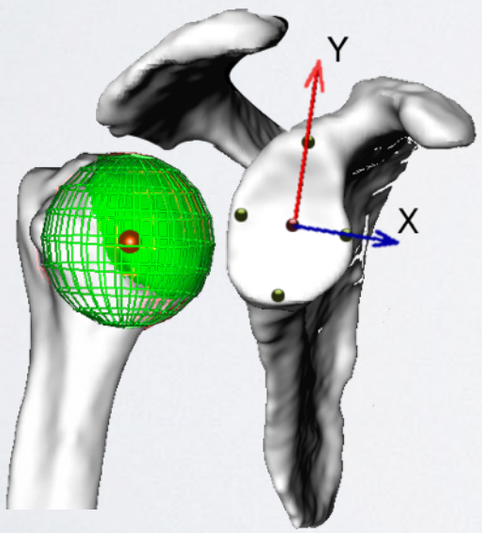
Non-Conforming Total Shoulder Arthroplasty

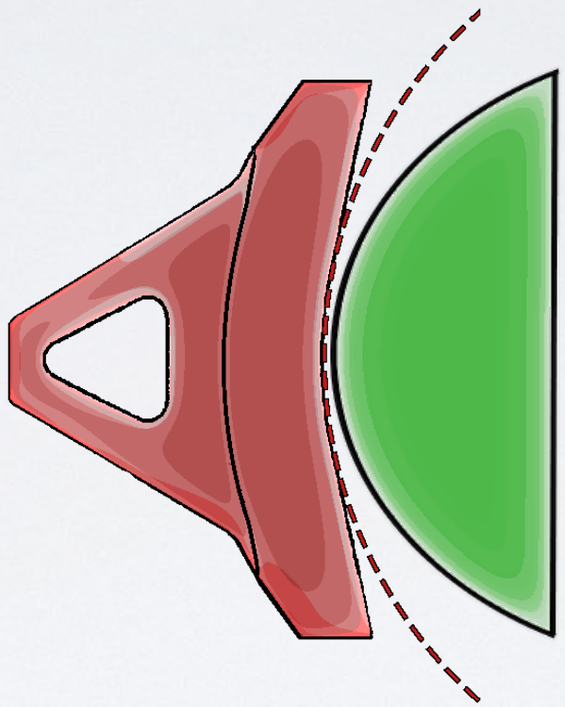
Mismatch = R_Glenoid - R_Head

Pros

Better reproduction of healthy GH joint kinematics
[Karduna, 1997]:

- 3 rotations
- 2 translations (AP: ±x // IS: ±y)

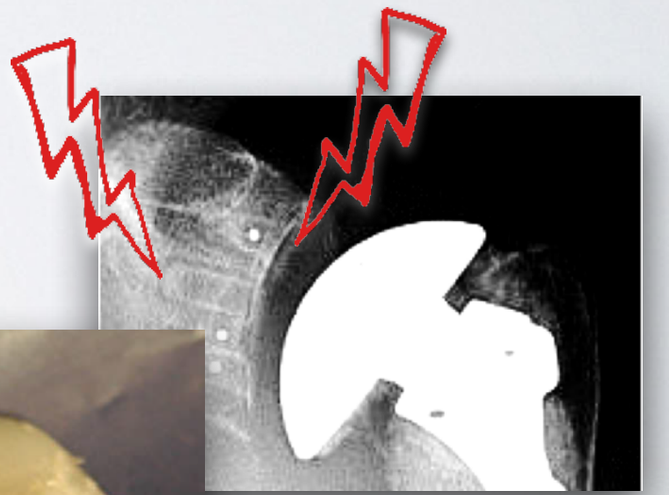


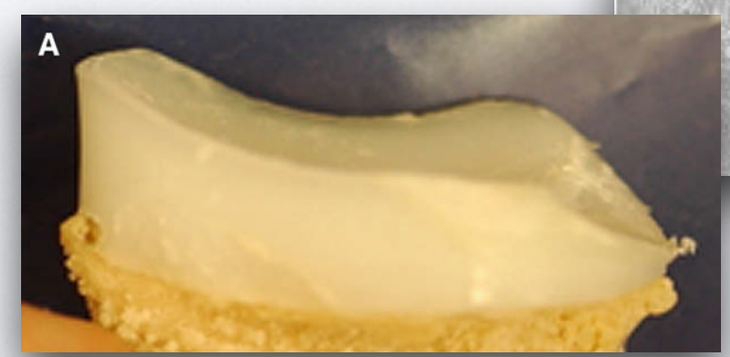


Cons

Main cause of first complications of NC-TSA
[Bohsali, 2006]

- Glenoid component loosening
- Glenoid plastic Wear





[Nho, 2008]

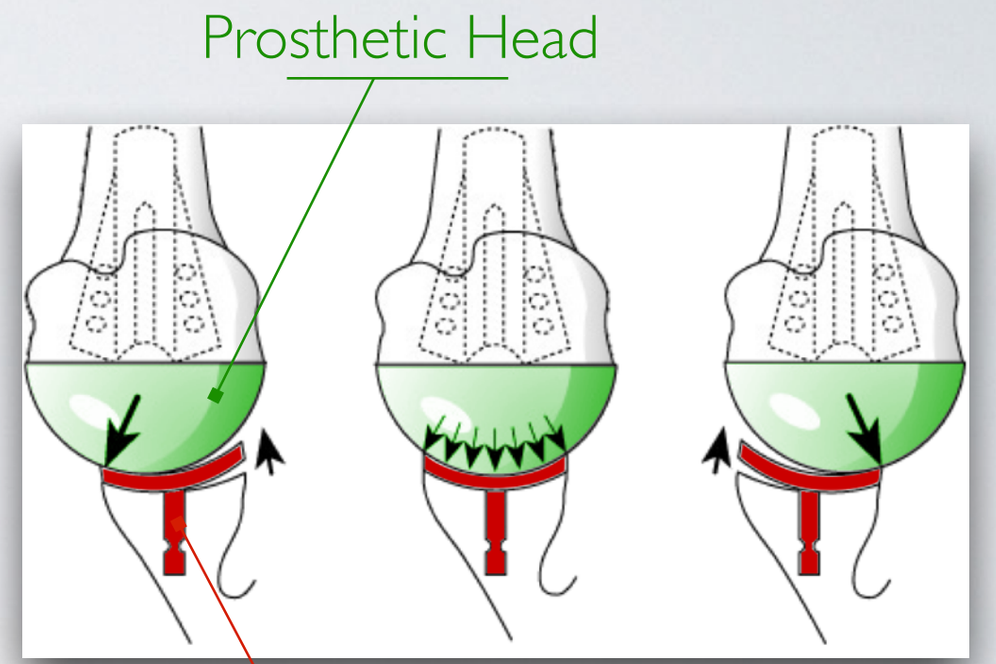
[Karduna, 1997] *J Bone Joint Surg Am*, **84-A**(12). pp. 2186–2191
[Nho, 2008] *J Shoulder Elbow Surg.* **17**(6), pp. 914–920.
[Bohsali, 2006] *J Bone Joint Surg*, **88**(10), p. 2279-92.

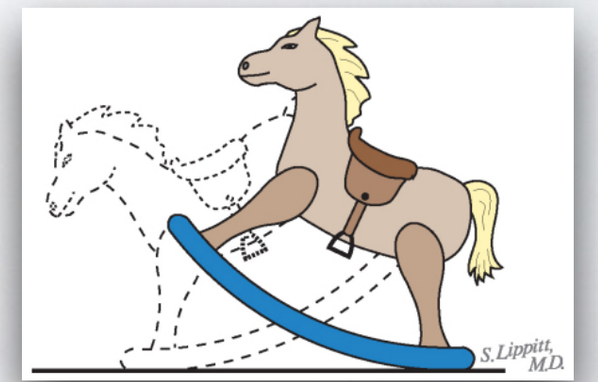
CONTEXT

COMPLICATIONS OF NC-TSA [Bohsali, 2006]

WHY ?

- **Linked to translations and forces:**
  - **Rocking horse effect**: main cause of **glenoid loosening** [Franklin, 1988]
    - Mismatch ➡ GH translations
    - Eccentric GH joint reaction force on the glenoid rim
    - Loss of fixation glenoid component - scapula bone





[Matsen, 2011]

[Bohsali, 2006] *J Bone Joint Surg*, **88**(10), p. 2279-92.
[Franklin, 1988] *J Arthroplasty*, **3**(1), pp. 39–46.
[Matsen, 2011] *http://shoulderarthritis.blogspot.com/*.

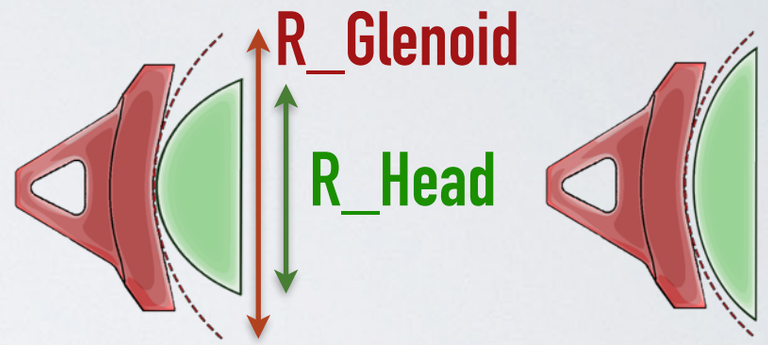
CONTEXT

COMPLICATIONS OF NC-TSA [Bohsali, 2006]

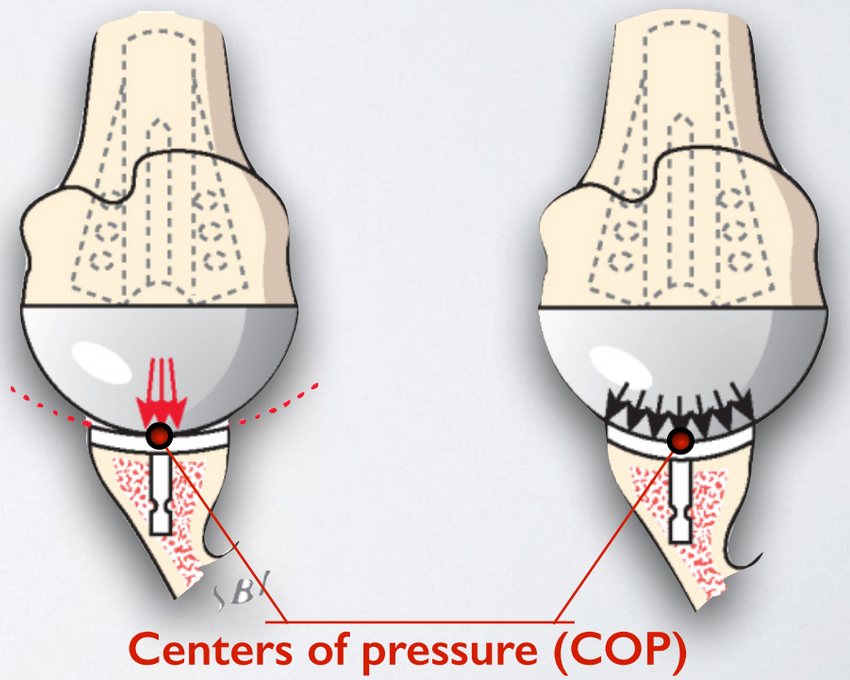
WHY ?

- **Linked to translations and forces:**
  - Rocking horse effect
    loosening
  - Impact on **wear** [Boyd, 1990]:
    - ⬆ translations ⇔ ⬆ wear
    - For a given GH reaction force:
      - If ⬇ contact area
      - Then ⬆ stress concentrations (Hooke's law : $\sigma = F/S$)

Mismatch = R_Glenoid - R_Head



Mismatch 1 > Mismatch 2



[Matsen, 2011]

[Bohsali, 2006] *J Bone Joint Surg*, **88**(10), p. 2279-92.
[Boyd,1990] *J Arthroplasty*, **5**(4), p. 329-336.
[Franklin, 1988] *J Arthroplasty*, **3**(1), pp. 39–46.
[Matsen, 2011] *http://shoulderarthritis.blogspot.com/*.

Context

Research Question and Objectives

Current recommendations: no clear consensus for the choice of mismatch

Study	Objective / Quantified parameter	Mismatch
In-Vitro [Karduna, 1997]	Better reproduction of healthy kinematic	4 mm
Radiographic [Walch, 2002]	Limit glenoid radiolucent lines (glenoid loosening)	5 to 10 mm
In-Vivo [Gleyze, 2013]	Correlation to any complication	3 to 4 mm

Research question:

What is the **optimum mismatch**
to **minimize glenoid loosening risk** and **wear**
while having small **humeral head translations** ?

[Gleyze,2013] *Rev. Chir. Orthop. Trauma.*, 99(7S), pp. S364.
[Karduna, 1997] *J Bone Joint Surg Am*, **84-A**(12). pp. 2186–2191
[Walch, 2002] *J Bone Joint Surg Am*, **79**(8). pp.1166–1174

CONTEXT

RESEARCH QUESTION AND OBJECTIVES

What is the **optimum mismatch**
to **minimize glenoid loosening risk** and **wear**
while having small **humeral head translations** ?

PARAMETER TO QUANTIFY		OBJECTIVE TO REDUCE WEAR AND GLENOID LOOSENING RISK
Humeral head Translations	IS and AP translations	Minimized
Contact prosthetic humeral head on glenoid component	Position of center of pressure (COP)	Centered
	GH joint reaction force (GH-JRF)	n/a
	Contact area (A)	n/a
	Pressure (P = GH-JRF/A)	Minimized

CONTEXT

RESEARCH QUESTION AND OBJECTIVES

What is the **optimum mismatch**
to **minimize glenoid loosening risk** and **wear**
while having small **humeral head translations** ?

≡ Objective and method:

- Develop a **musculoskeletal model** for inverse dynamic analysis adapted to the NC-TSA context:
  - Simulation of **humeral head translations**
  - Integration of **prosthetic components** (humeral head and glenoid components)

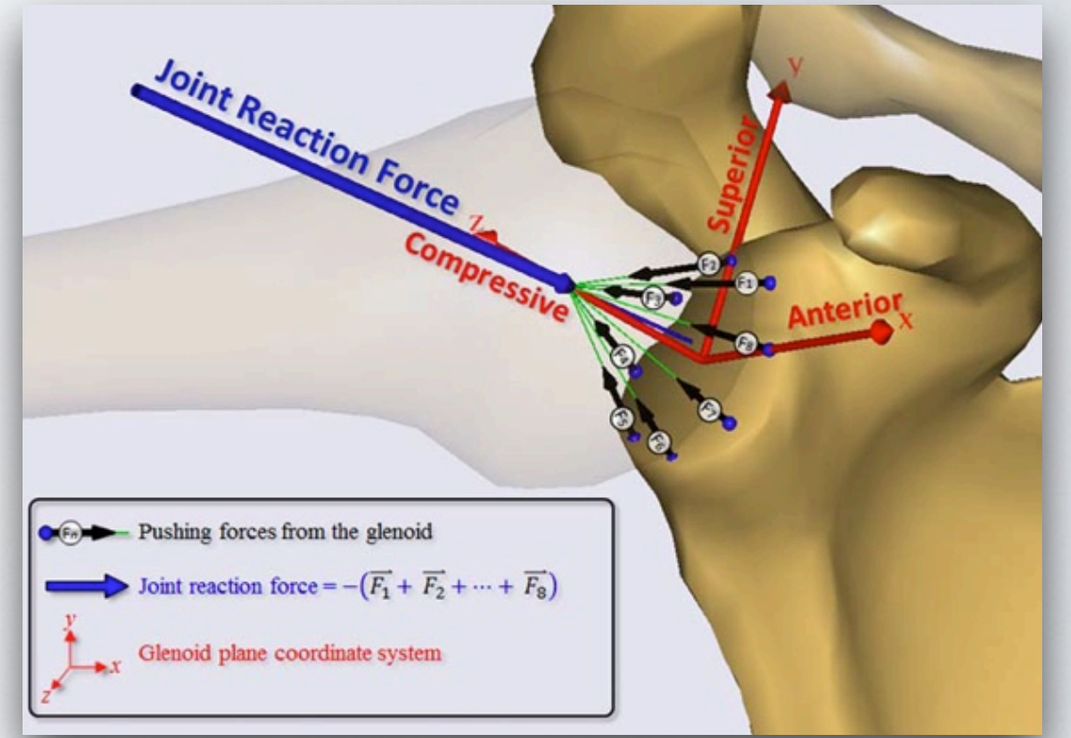
- Quantify **parameters responsible of glenoid loosening** and wear
  - **Humeral head translations:** IS & AP range
  - **Contact of the humeral head on the plastic glenoid component** :
    - Center of pressure position (COP)
    - GH joint reaction force (GH-JRF)
    - Contact area
    - Contact pressure

Shoulder Model

Current AnyBody™ Shoulder Model

Constraints at the GH joint:

- No humeral head translation relative to the glenoid
- No glenohumeral contact surface computation
- Glenohumeral joint reaction force trajectory enforced to stay inside the glenoid



[Lemieux, 2013]

[Lemieux, 2013] *Comput Methods Biomech Biomed Engin.* **16**(1). pp. 37-41

Shoulder Model

Current AnyBody™ Shoulder Model

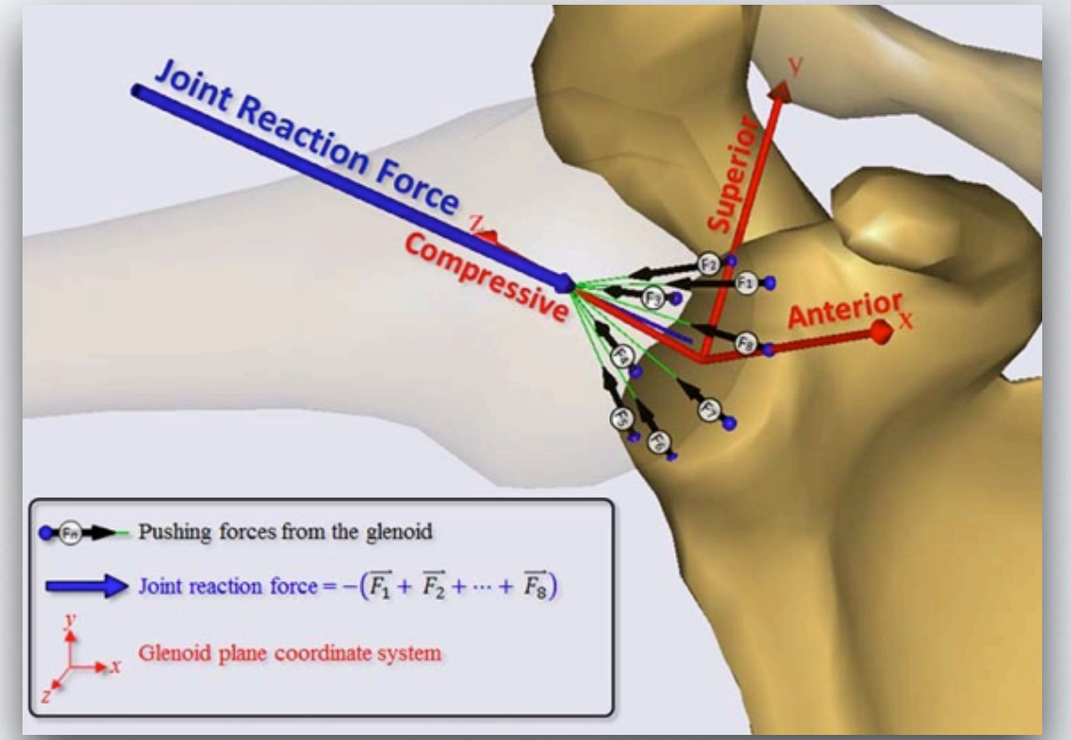
Constraints at the GH joint:

- No humeral head translation relative to the glenoid

1. Ball & Socket Constraint

- No glenohumeral contact surface computation
- Glenohumeral joint reaction force trajectory enforced to stay inside the glenoid

2. Stability Constraint



[Lemieux, 2013]

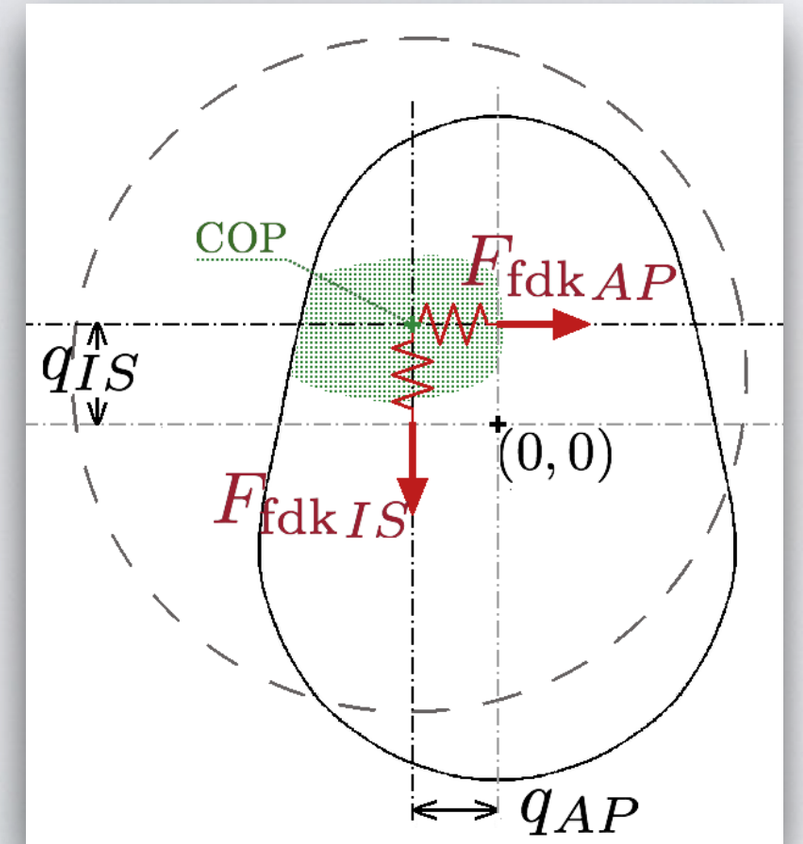
[Lemieux, 2013] *Comput Methods Biomech Biomed Engin.* **16**(1). pp. 37-41

Shoulder Model

Humeral Head Translations

~~1. Ball & Socket Constraint~~

- No humeral head translations



1. Force Dependent Kinematic [Andersen,2011]

- **Objective : Simulate GH translations** (IS & AP directions)
  - GH joint = 5 DoF
  - Simultaneously compute muscle + joint forces as well as joint kinematics
  - Quasi static force equilibrium in selected DoF, i.e. IS & AP directions (q_{fdkIS} et q_{fdkAP})

- **Non linear elastic springs to simulate joint behaviour**

  [Bigliani, 1992] [Warner, 1999]:

$$\begin{cases} F_{\text{fdk}\,IS} = 5.62 - 1.68\ q_{IS} - 1.121.68\ q_{IS}^2 \\ \qquad\qquad +0.9\ q_{IS}^3 - 0.01\ q_{IS}^4 \\ F_{\text{fdk}\,AP} = 5.62 - 1.68\ q_{AP} - 1.121.68\ q_{AP}^2 \\ \qquad\qquad +0.9\ q_{AP}^3 - 0.01 q_{AP}^4 \end{cases}$$

[Bigliani,1992] *J of Orth Res*, **10**(2), pp. 187–197
[Warner,1999] *J Biomech Eng*, **121**(3), pp. 311–315

Shoulder Model

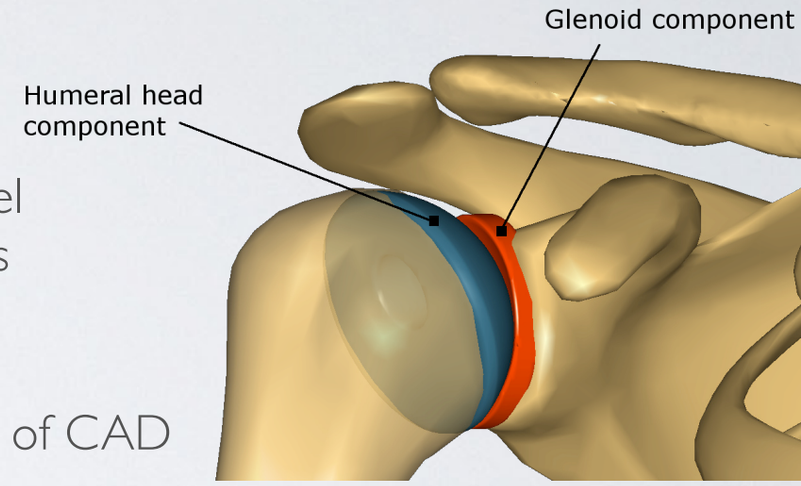
Surface Contact

~~2. Stability constraint~~

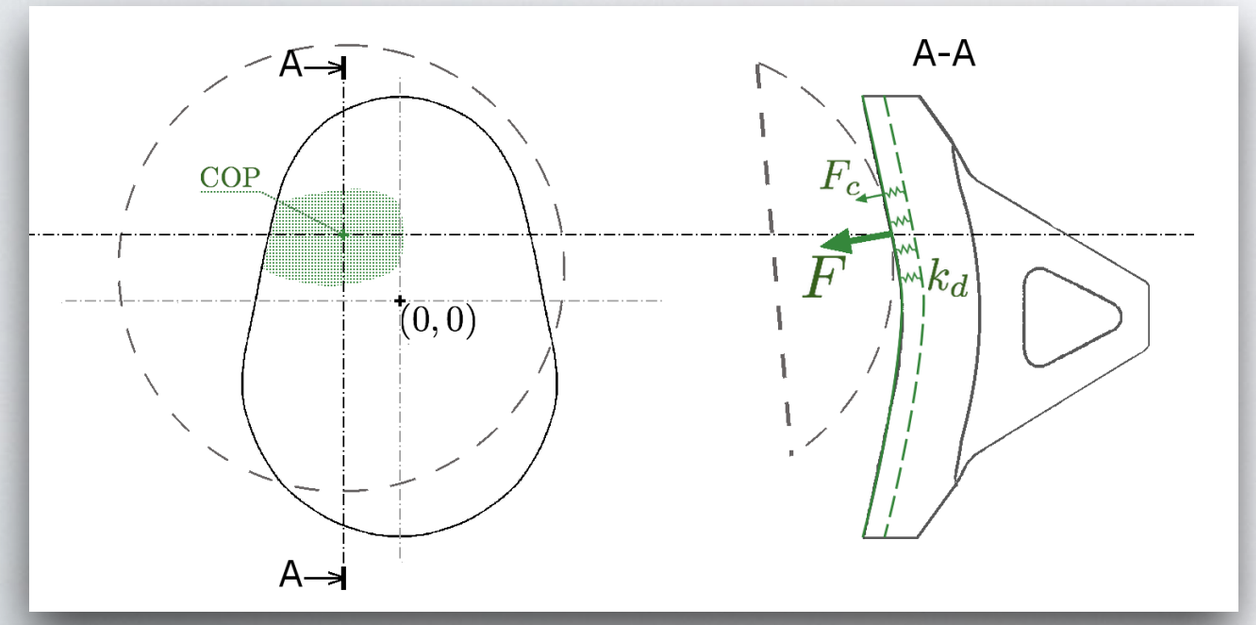
- No GH contact computation
- Glenohumeral joint reaction force trajectory enforced to stay inside the glenoid

2. Surface Contact

- **Implants:**
  - Head and glenoid components
  - CAD Models (*.stl) : Surface model composed of triangles and vertices

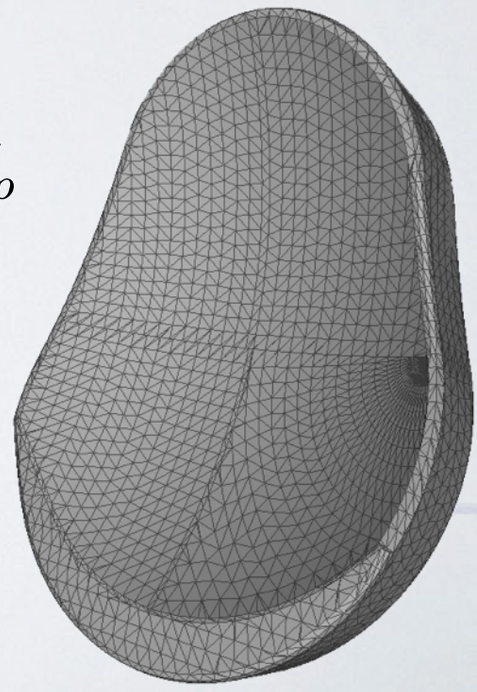


- **Computation:**
  - Contact force F_c between vertices of CAD models (rigid model, k_d stiffness)
  - GH-Joint reaction force: F (GH-JRF) [Li, 1997]



$$F[N] = \sum F_c[N] = k_d * V_p$$

$$k_d = \frac{(1-\nu)*E}{(1+\nu)(1-2\nu)h}$$



[Li, 1997] *J biomech*, **30**(6), pp. 635–638

Shoulder Model

Simulations

Simulations:

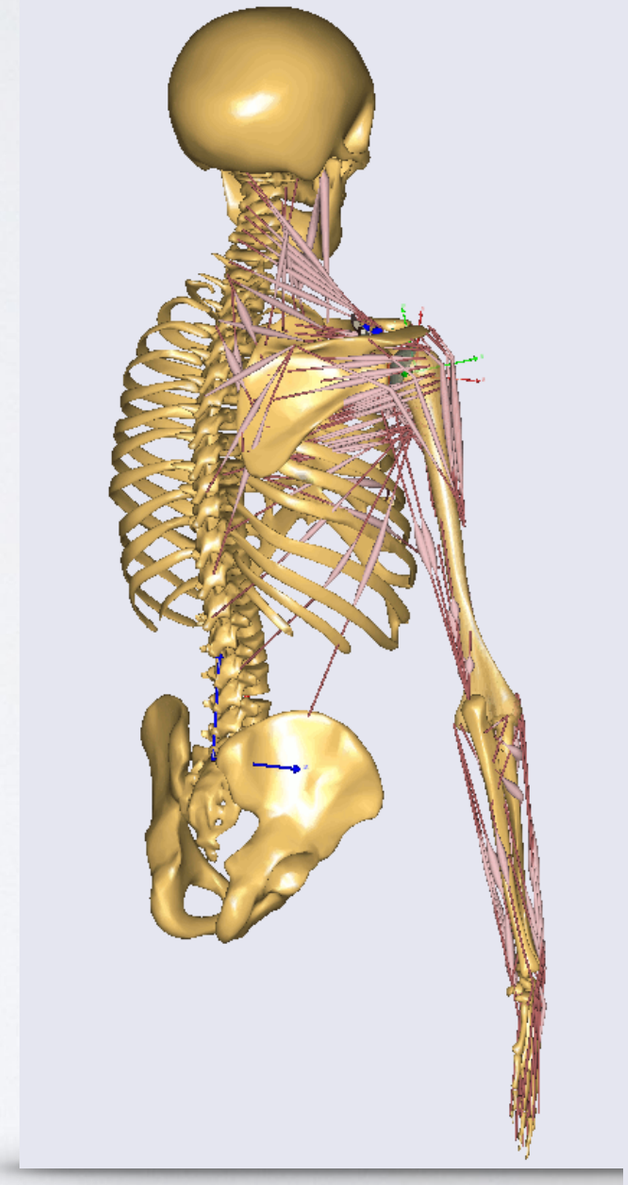
- Elevation in the scapular plane (abduction)
- Scapulo-Humeral Rhythm [De Groot, 2001]

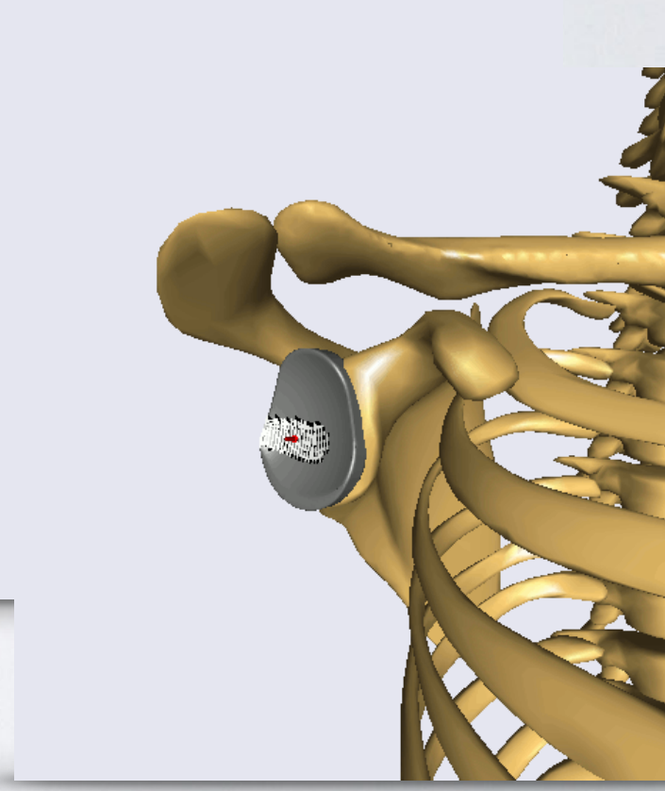
Objective:

- Effect of mismatch on glenoid loosening risk (humeral head translations + contact mechanics)

Test of 5 available mismatches:

1.4mm, 3.4mm, 6.4mm, 8mm, 9.6mm





[De Groot, 2001] *Clin Biomech*, **16**(9), pp. 735–743

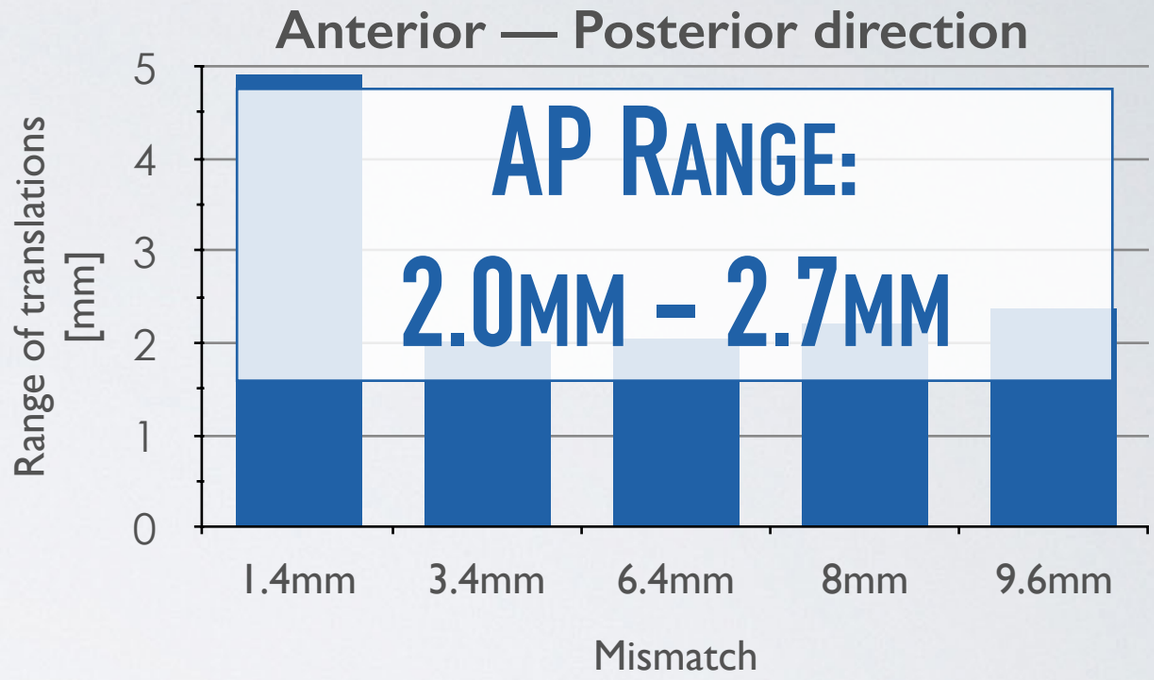
RESULTS

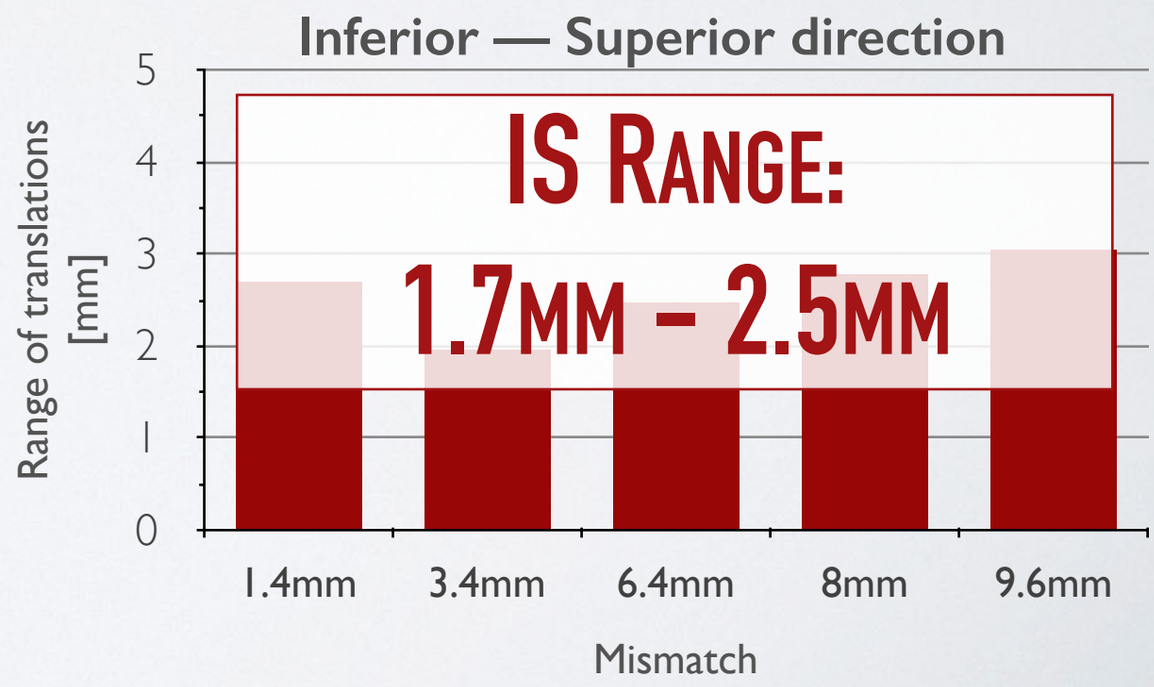
HUMERAL HEAD TRANSLATIONS

OBSERVATIONS

Comparison with literature

- ★ Same order of magnitude for the AP direction:
  - In-vivo [Bey, 2008]: 2.6mm
  - In-vivo [Graichen, 2000; 2005]: 1-2mm
- ★ Same order of magnitude for the IS direction:
  - In-vivo [Bey, 2008]: 2.0mm





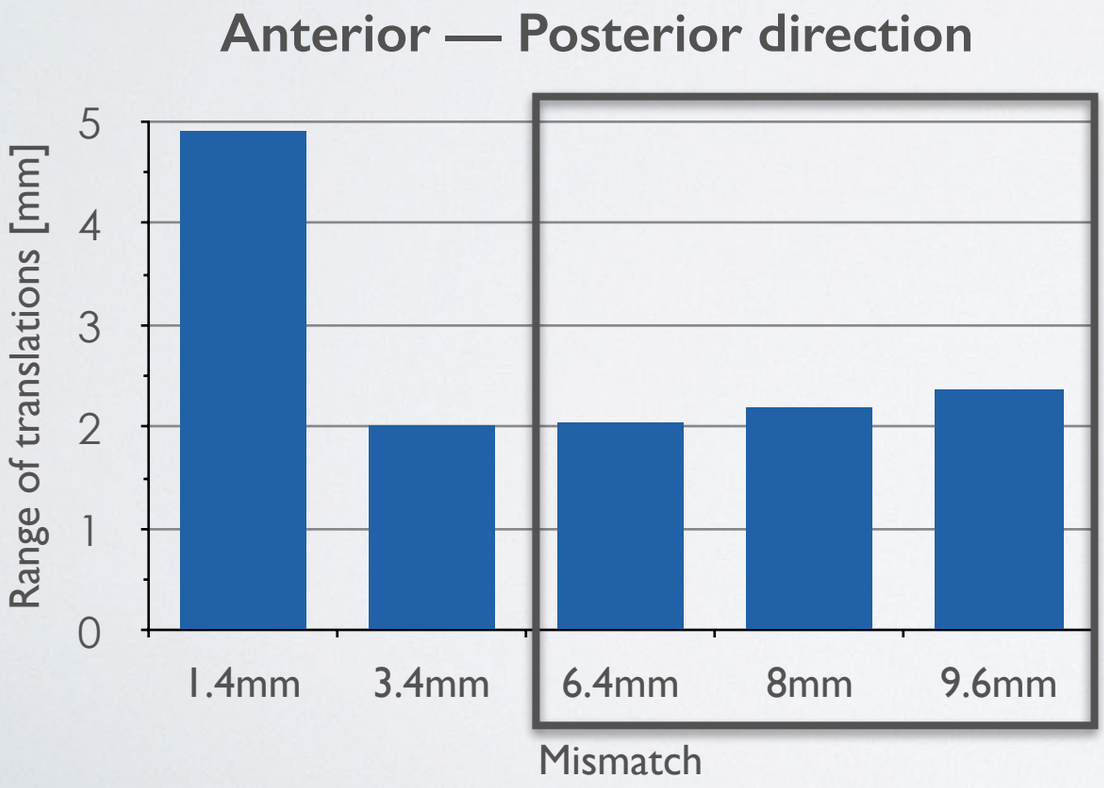
[Bey, 2008] *J Biomech*, **41**(3), pp. 711–714.
[Graichen, 2000] *J Biomech*, **33**(5), pp. 609–613.
[Graichen, 2005] *J Biomech*, **38**(4), pp. 775–760.

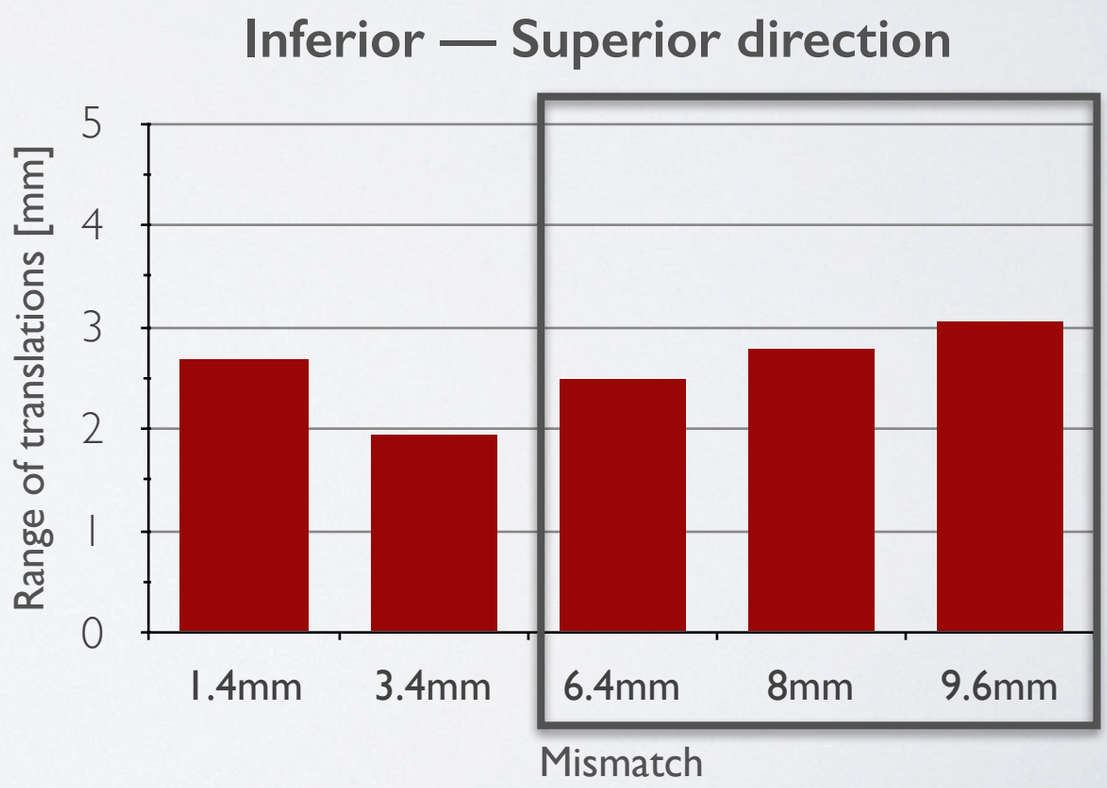
RESULTS

HUMERAL HEAD TRANSLATIONS

Effect of mismatch on HH translations

PARAMETER	OBJECTIVE	OBSERVATIONS
Range of translations IS & AP	To minimize	Small effect for recommended mismatches (5mm to 10mm)



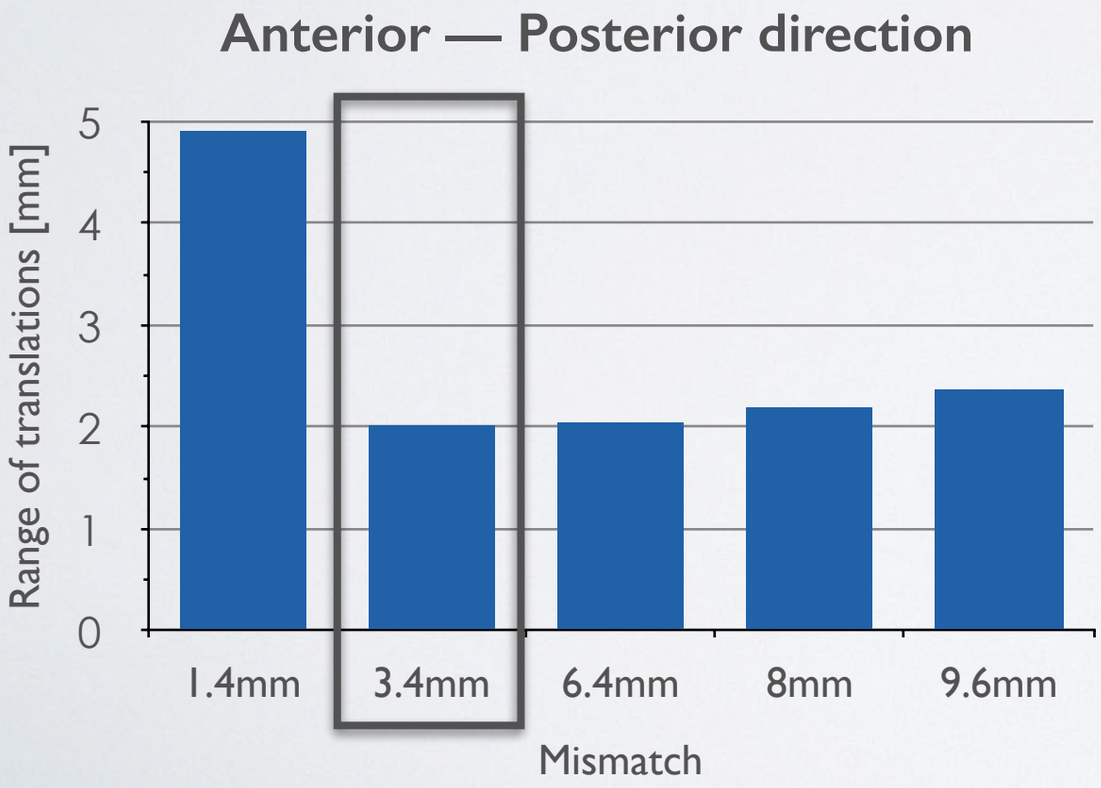


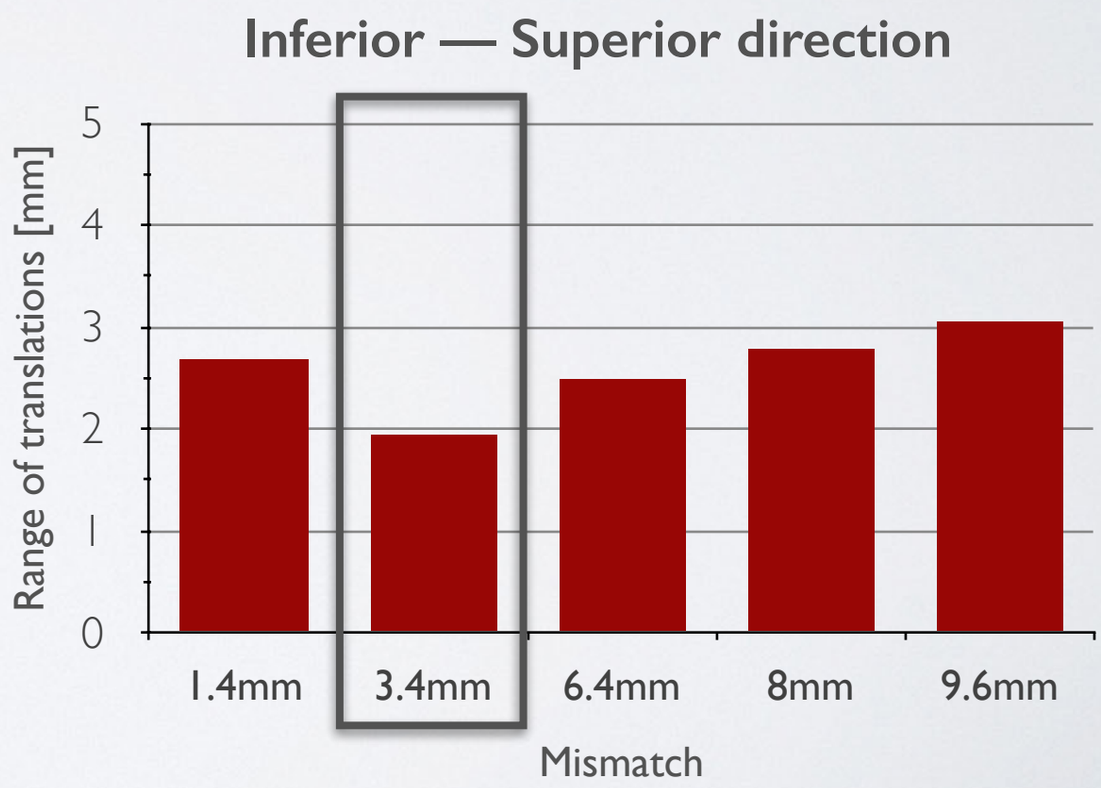
RESULTS

HUMERAL HEAD TRANSLATIONS

Effect of mismatch on HH translations

PARAMETER	OBJECTIVE	OBSERVATIONS
Range of translations IS & AP	To minimize	Small effect for recommended mismatches (5mm to 10mm)
		Optimum: 3.4 mm



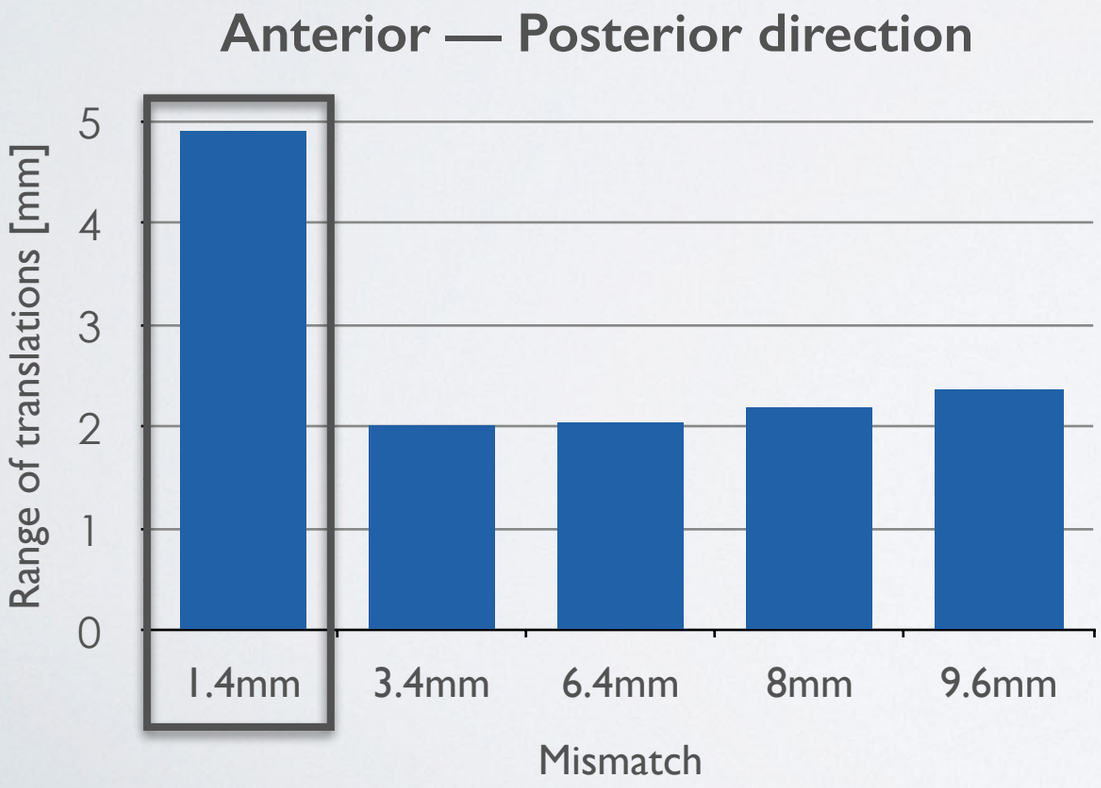


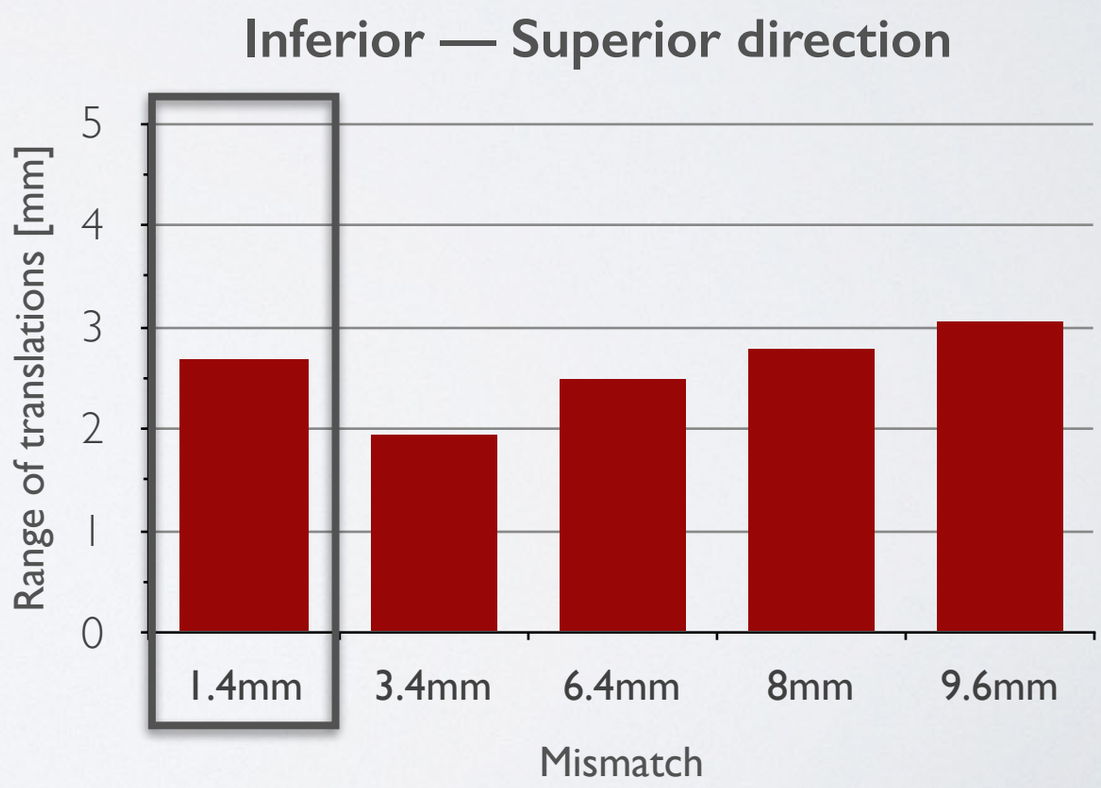
RESULTS

HUMERAL HEAD TRANSLATIONS

Effect of mismatch on HH translations

PARAMETER	OBJECTIVE	OBSERVATIONS
Range of translations IS & AP	To minimize	Small effect for recommended mismatches (5mm to 10mm)
		Optimum: 3.4 mm
		Case: 1.4 mm



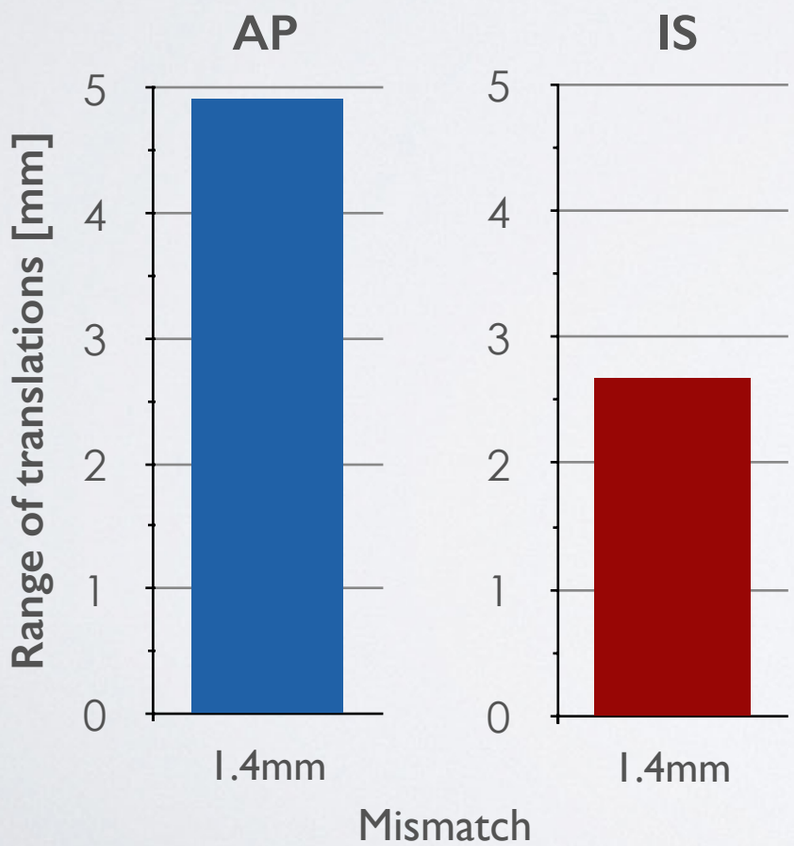


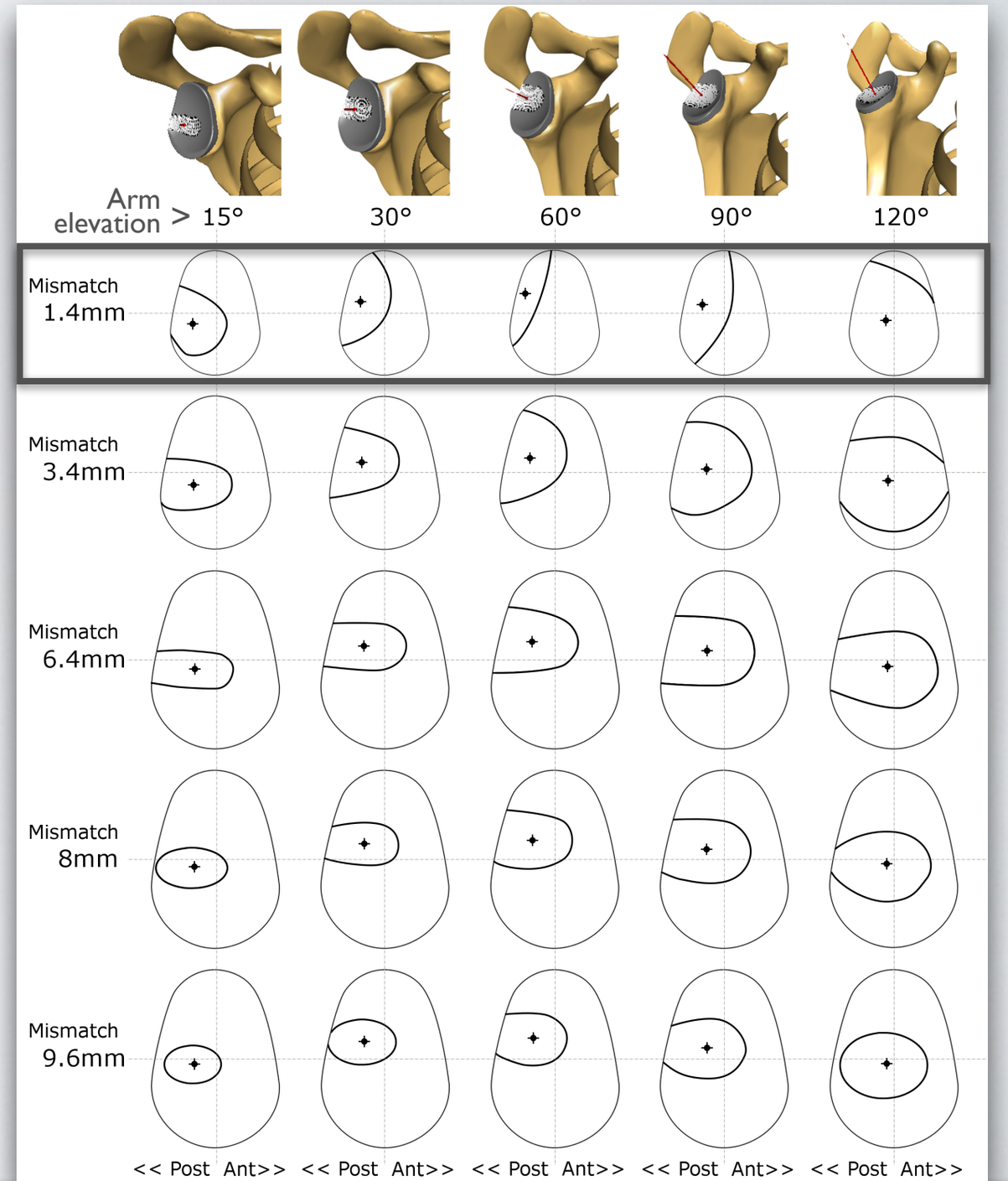
RESULTS

HUMERAL HEAD TRANSLATIONS

Effect of mismatch on HH translations

OBSERVATIONS
Small effect for recommended mismatches (5mm to 10mm)
Optimum: 3.4 mm
Case 1.4 mm





RESULTS

CONTACT: HUMERAL HEAD ON GLENOID COMPONENT

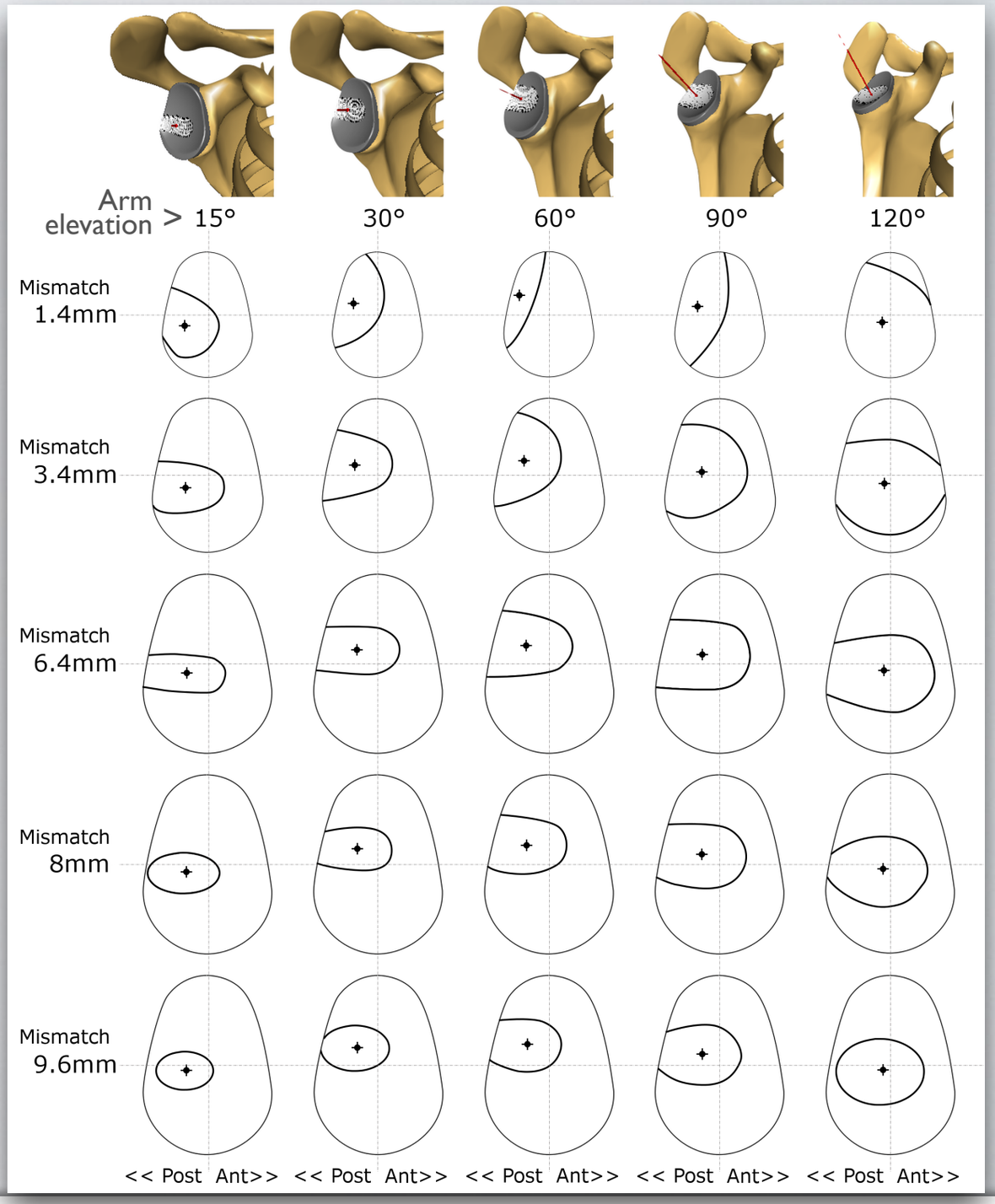
PARAMETER	OBJECTIVE
COP Position	Centered

OBSERVATIONS

Comparison with literature

Posterior — Superior position

- ★ Numerical study [Patel, 2014]
- ★ InVivo/clinical study [Massimini, 2010]
- ★ Aspect of retrieved glenoid components [Hertel, 2003] [Nho, 2008]



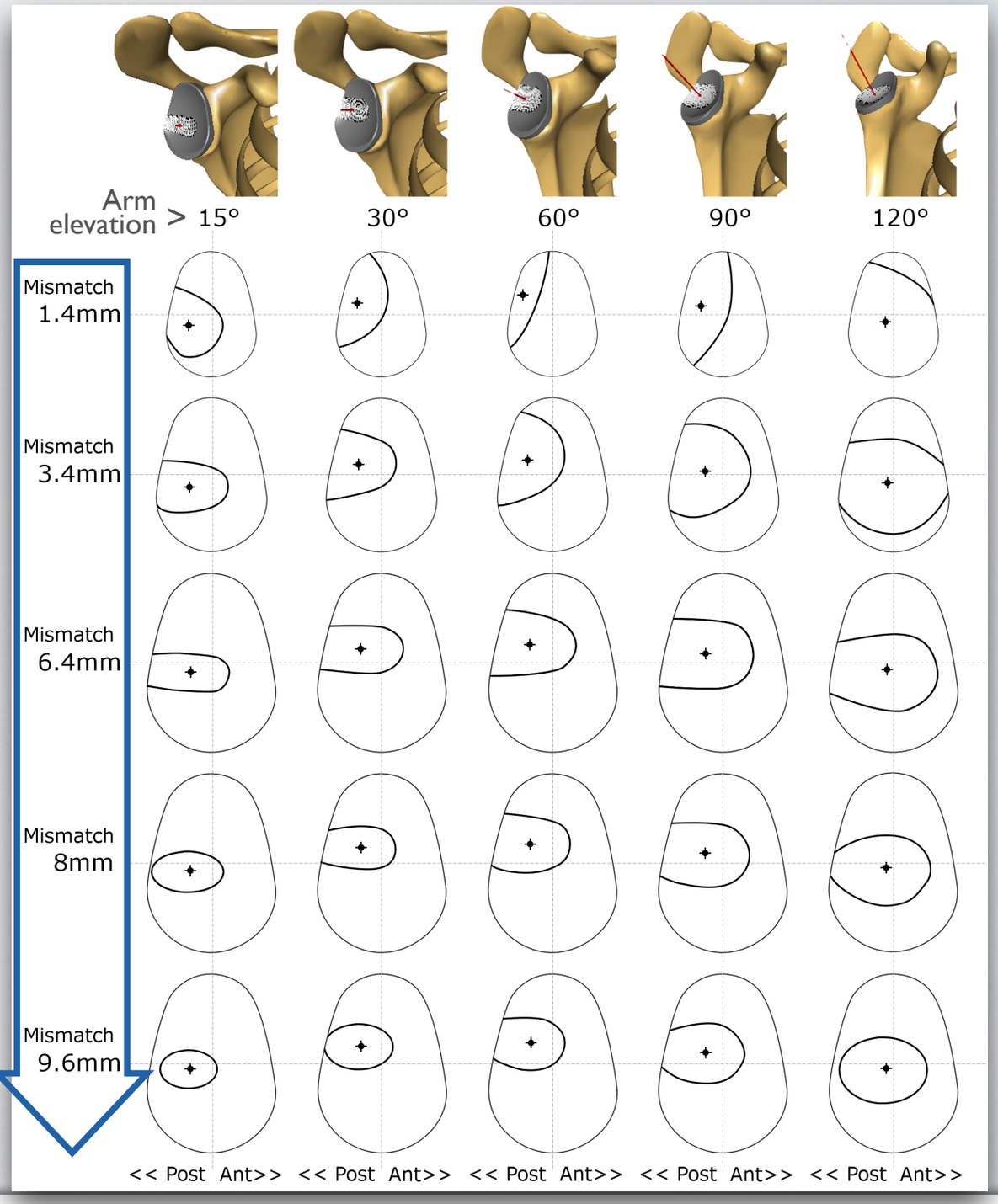
RESULTS

CONTACT: HUMERAL HEAD ON GLENOID COMPONENT

PARAMETER	OBJECTIVE
COP Position	Centered

OBSERVATIONS

Comparison with literature	Posterior — Superior position ★ Numerical study [Patel, 2014] ★ InVivo/clinical study [Massimini, 2010] ★ Aspect of retrieved glenoid components [Hertel, 2003] [Nho, 2008]
Mismatch Effect	Small effect



[Hertel, 2003] *J Arthroplasty*, **18**(3), pp. 361–366.
[Massimini, 2010] *J Bone Joint Surg Am.*, **92**(4), pp. 916–926.
[Nho, 2008] *J Shoulder Elbow Surg.* **17**(6), pp. 914–920.
[Patel, 2014] *J Shoulder Elbow Surg.* **In Press**. pp. 1–7.

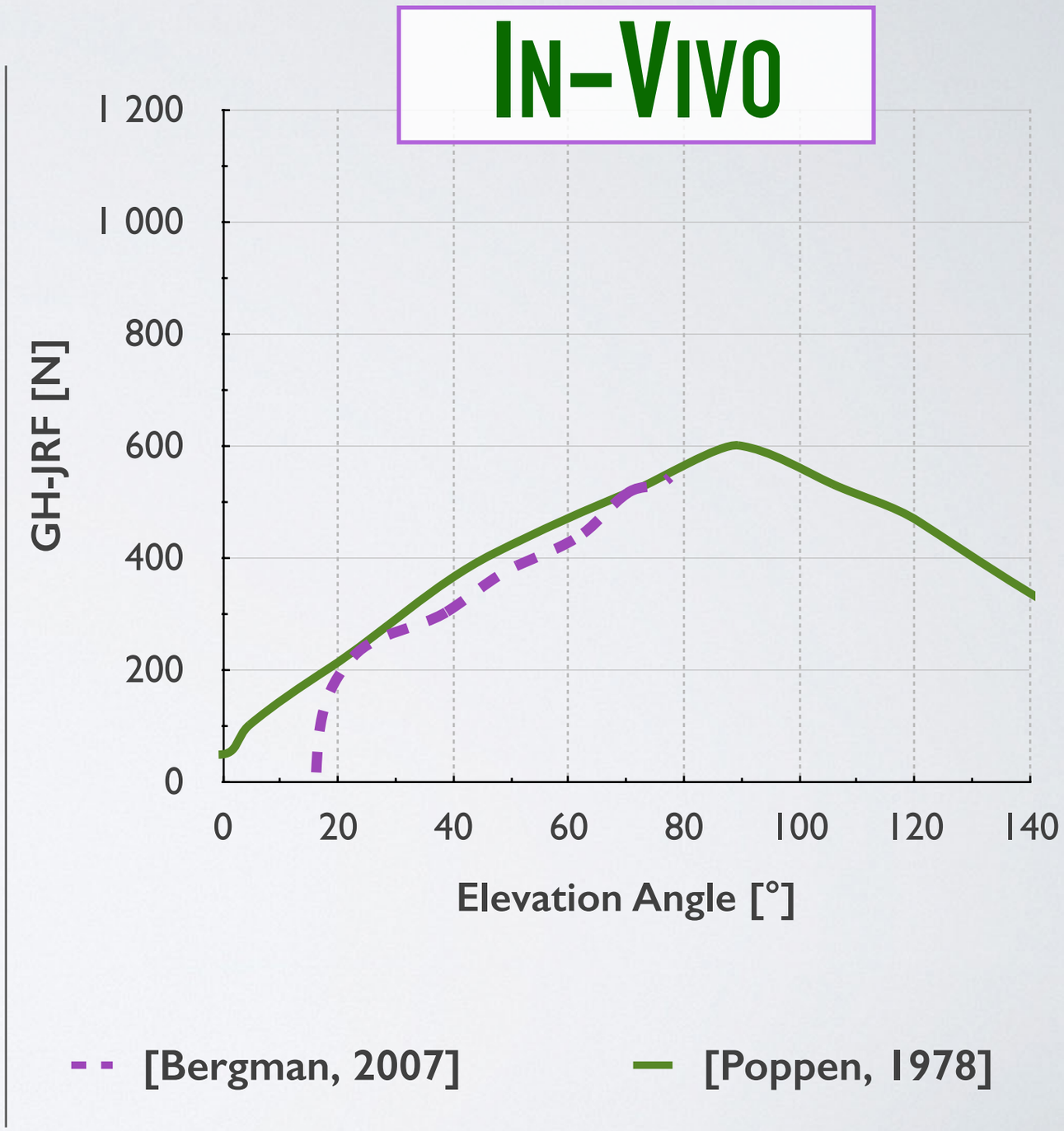
RESULTS

CONTACT: HUMERAL HEAD ON GLENOID COMPONENT

PARAMETER	OBJECTIVE
COP Position	Centered
Joint reaction force GH-JRF	-

OBSERVATIONS

Comparison with literature	⋆ In-vivo, instrumented implant [Bergmann, 2007] ⋆ In-vivo, analytic [Poppen, 1978]



[Bergmann, 2007] *J biomech*, **40**(10), pp. 2139–2149
[Poppen, 1978] *Clin orthop rel res*, **135**, pp. 165–70

RESULTS

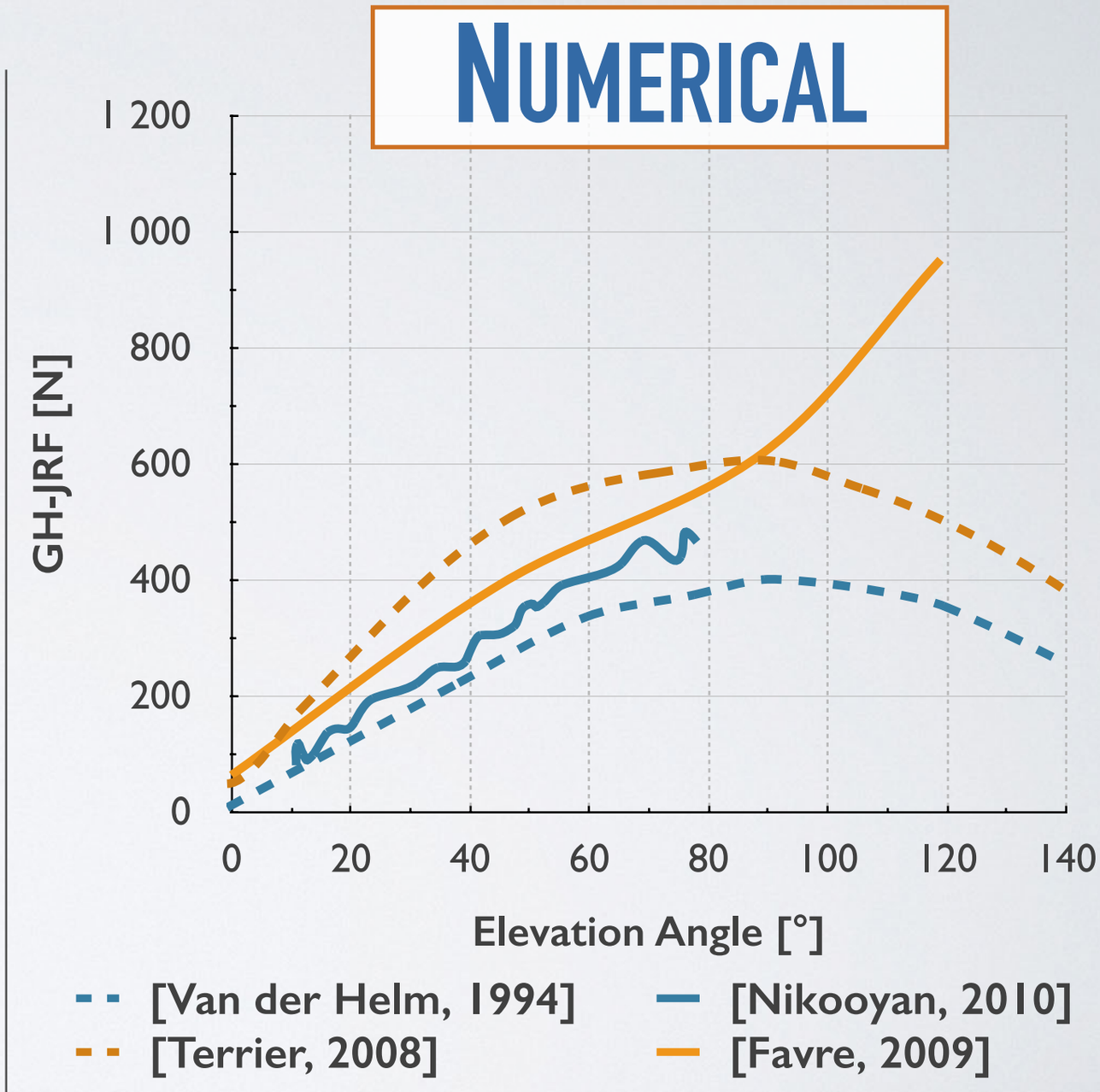
CONTACT: HUMERAL HEAD ON GLENOID COMPONENT

PARAMETER	OBJECTIVE
COP Position	Centered
Joint reaction force GH-JRF	-

OBSERVATIONS

Comparison with literature

- ⋆ In-vivo, instrumented implant [Bergmann, 2007]
- ⋆ In-vivo, analytic [Poppen, 1978]
- ⋆ Numerical studies [Terrier, 2013] [Terrier, 2008] [Favre, 2009] [Van der Helm, 1994] [Nikooyan, 2010]



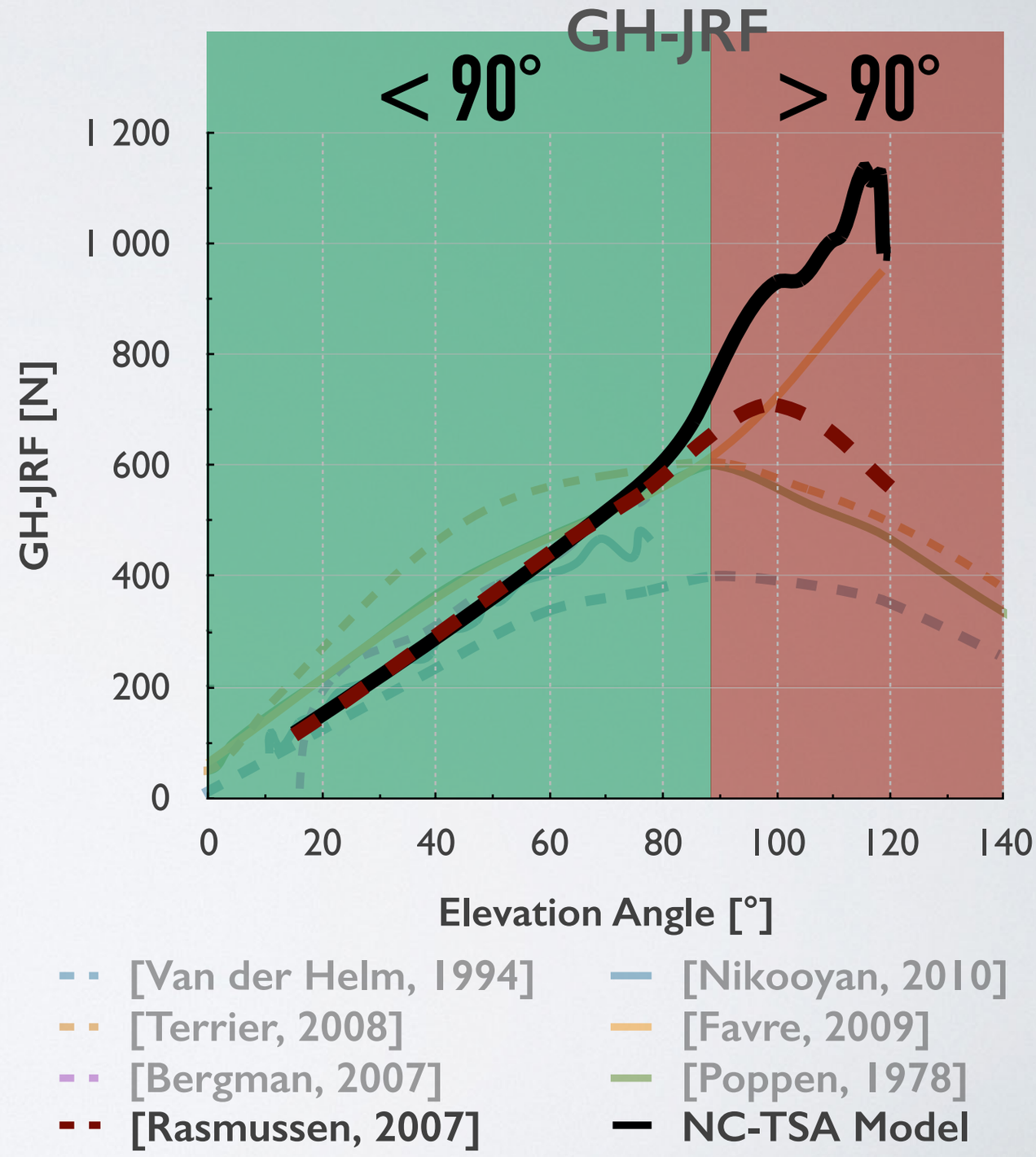
[Favre, 2009] *Philos Trans A Math Phys Eng Sci,* **367**(1895), pp. 2095–2118.
[Nikooyan, 2010] *J biomech,* **43**(15), pp. 3007–3014
[Terrier, 2008] *Med eng & phys*, **30**, pp. 710–716
[Terrier, 2013] *Clin Biomech*, **28**(2), pp. 146–150
[Van der Helm, 1994] *J Biomech,* **27**(5), pp. 551–569

RESULTS

CONTACT: HUMERAL HEAD ON GLENOID COMPONENT

PARAMETER	OBJECTIVE
COP Position	Centered
Joint reaction force GH-JRF	-

OBSERVATIONS	
Comparison with literature	<u>≤90°</u> - Same order of magnitude ★ In-vivo, instrumented implant [Bergmann, 2007] ★ In-vivo, analytic [Poppen, 1978] ★ Numerical studies [Terrier, 2013] [Terrier, 2008] [Favre, 2009] [Van der Helm, 1994] [Nikooyan, 2010] ★ AnyBody [Rasmussen, 2007] <u>≥90°</u> - Questionable !



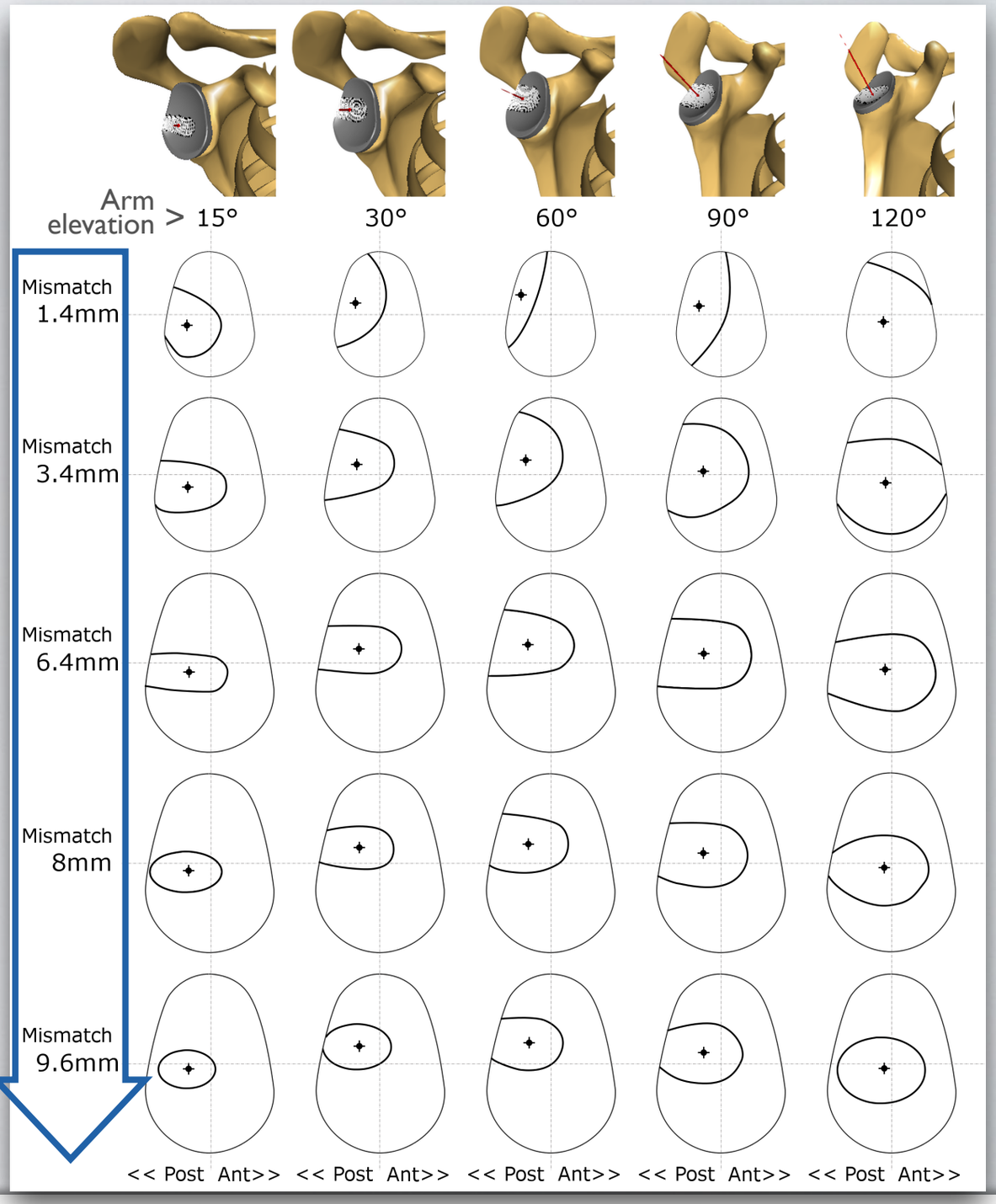
[Rasmussen, 2007] *J biomech*, **40**(Supplement 2), p. S67. In *ISB* (Taipei, Taiwan).

RESULTS

CONTACT: HUMERAL HEAD ON GLENOID COMPONENT

PARAMETER	OBJECTIVE
COP Position	Centered
Joint reaction force GH-JRF	-
Contact Area (A)	-

OBSERVATIONS	
General	⬆ contact area with ⬆ elevation angle ⋆ In-vitro [Hammond, 2012] [Soslowsky, 1992]
Effect Mismatch	⬇ contact area with ⬆ mismatch



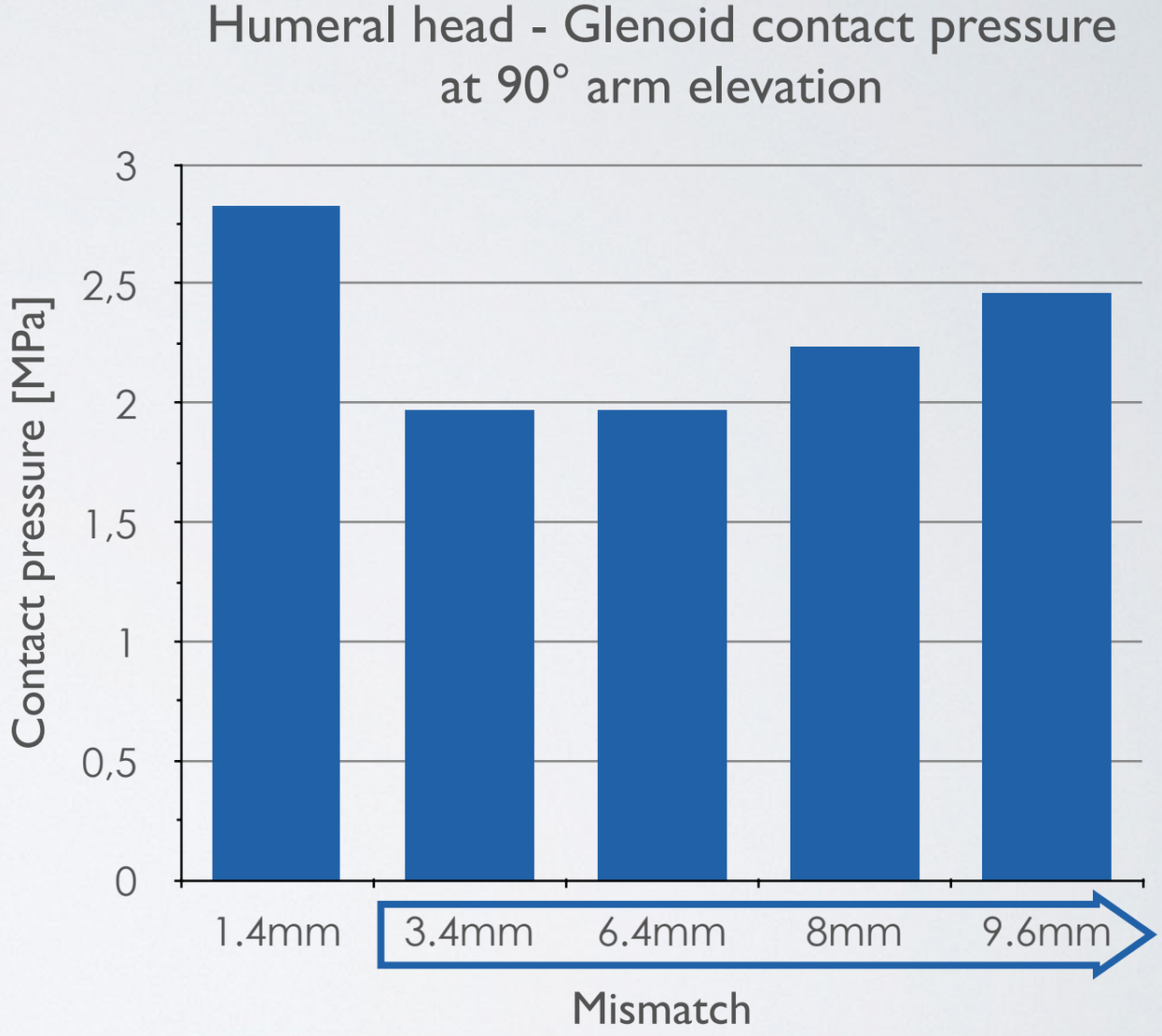
[Hammond, 2012] *J Bone Joint Surg Am*, **94**(1), pp. 68–76
[Soslowsky, 1992] *J Orthop Res*, **10**(4), pp. 524–534

RESULTS

CONTACT: HUMERAL HEAD ON GLENOID COMPONENT

PARAMETER	OBJECTIVE
COP Position	Centered
Joint reaction force GH-JRF	-
Contact Area (A)	-
Contact pressure (P=GH-JRF/A)	Minimized

OBSERVATIONS	
Effect Mismatch	⬆ pressure with ⬆ mismatch ★ Numerical study (FE) [Hopkins, 2007]



[Hopkins, 2007] *J Biomech Eng*, **129**(2), pp. 223–230

RESULTS

CONTACT: HUMERAL HEAD ON GLENOID COMPONENT

PARAMETER	OBJECTIVE
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Joint reaction force GH-JRF	-
Contact Area (A)	-
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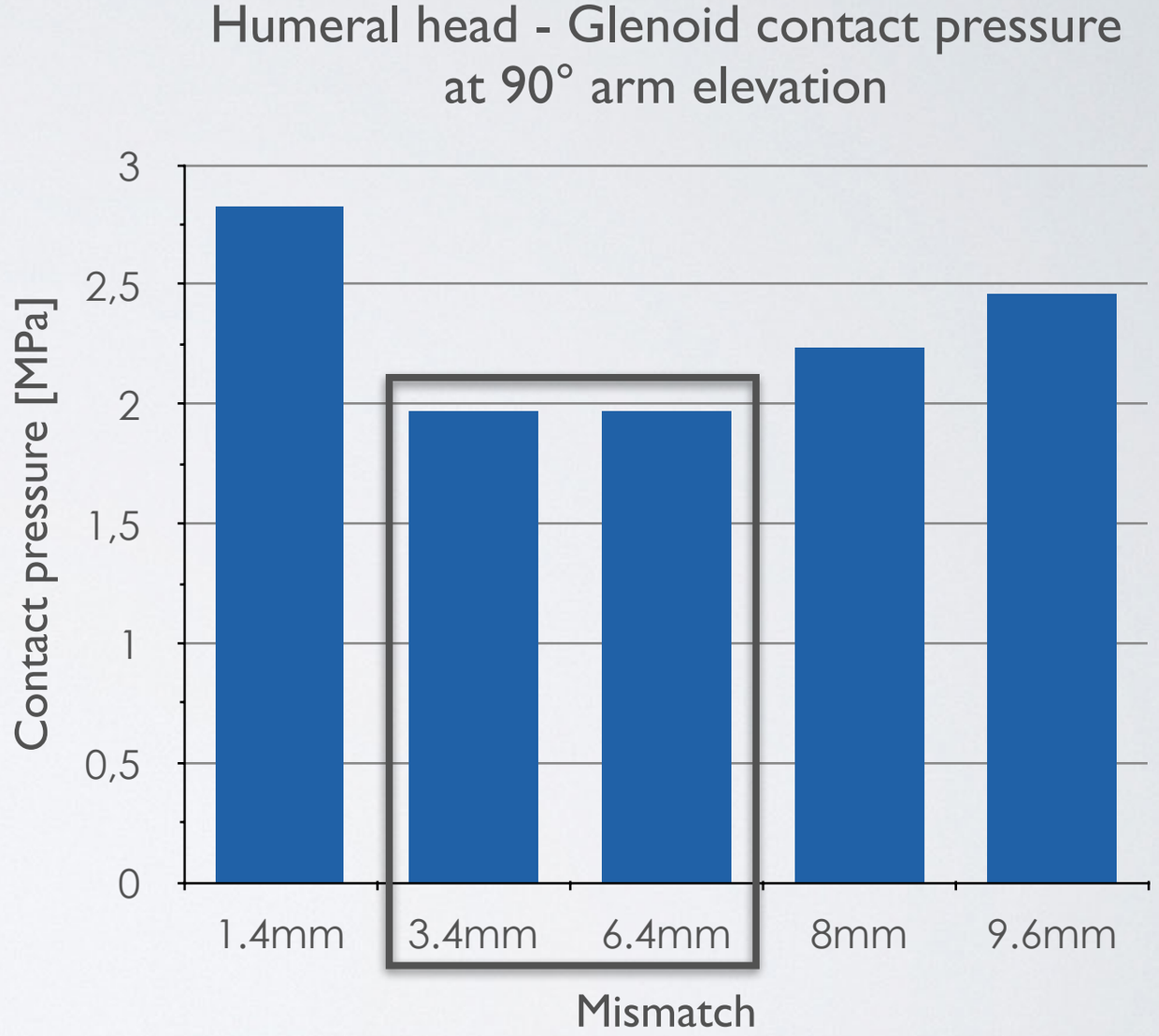
OBSERVATIONS	
Effect Mismatch	⬆ pressure with ⬆ mismatch ⋆ Numerical study (FE) [Hopkins, 2007]
Effect Mismatch	Optimum: 3.4 mm or 6.4 mm



[Hopkins, 2007] *J Biomech Eng,* **129**(2), pp. 223–230

Discussion / Conclusion

Contributions

Modeling:

Numerical musculoskeletal **model** adapted to **NC-TSA** context:

- Simulation of small **humeral head translations**
- Simulation of **contact** between humeral head and glenoid components
- Elements of **validation** based on the literature

Orthopaedic surgery:

- Evaluation of factors responsible for arthroplasty complications.
- In this study: effect of mismatch on « **glenoid loosening risk** »
  (HH translation + contact pattern):
  - Small effect for **recommended mismatches** (5-10mm)
  - **Optimum**: minimal HH translations
    & minimal contact pressure
  - **Critical**: eccentric humeral head position
    & maximal HH translations
    & maximal contact pressure

Recommended Mismatches: ✔

Optimum: Mismatch = 3.4 mm

Critical: Mismatch = 1.4 mm

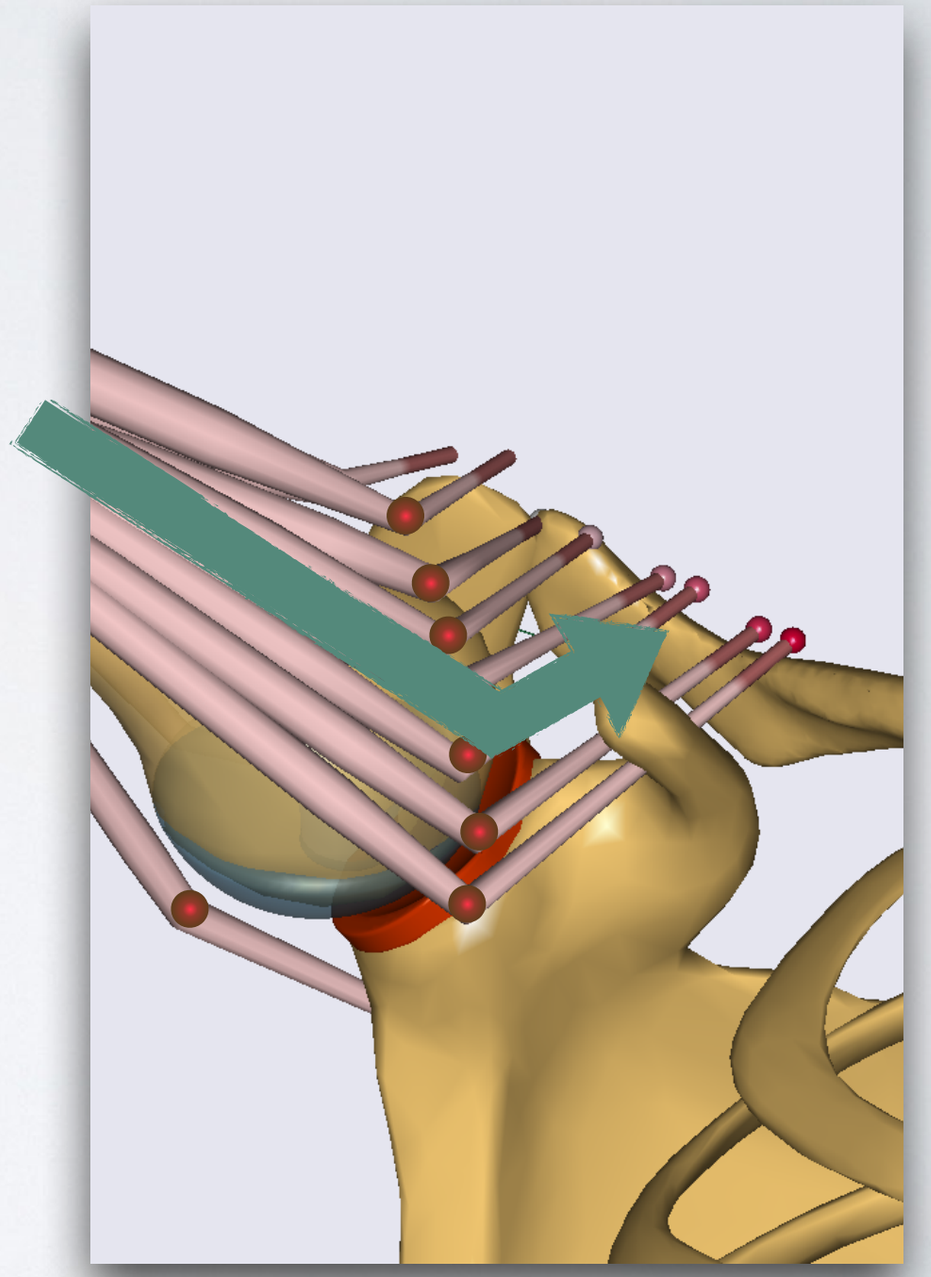
Discussion / Conclusion

Limitations

Deltoid modeling

- **Limitation above 90°** of arm elevation:
  - The rake problem: via-points position and V-shape
  - Consequences :
    - Anterior deltoid musculaire forces close to 0
    - Responsible for the GH-JRF overestimation?

- **Proposed work:** deltoid modeling modification:
  - Via-points depending on arm elevation
  - Muscular mesh



Discussion / Conclusion

Limitations

Deltoid modeling

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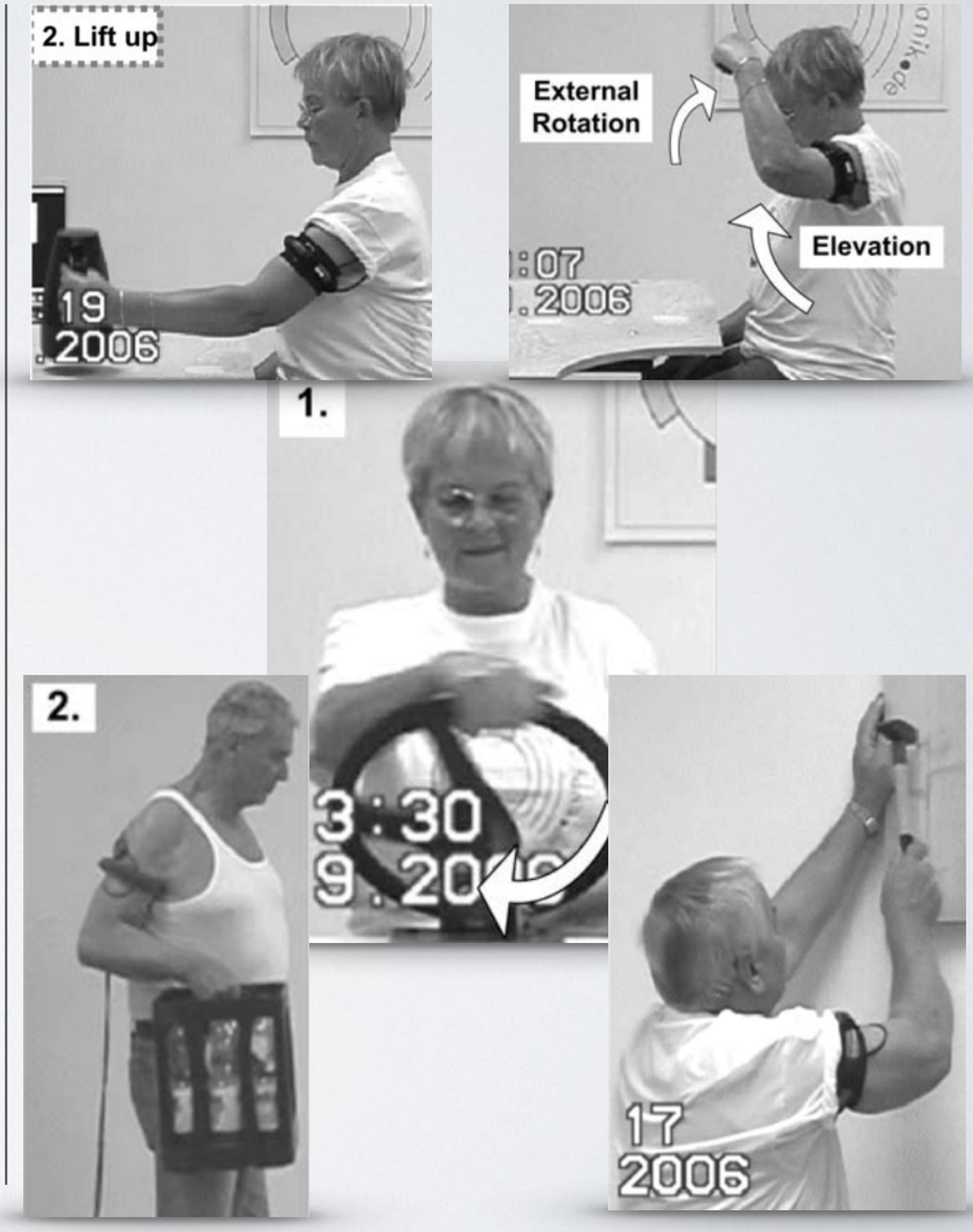

Input kinematic

- **Arm elevation** only
- Interest in **daily living activities**; use of literature data to simulate and validate the implementation

Discussion / Conclusion

Outlook & Future work

Musculoskeletal model for clinical (research) use:

- Need expressed by orthopaedic surgeons

  → **User interface:** adaptation of the shoulder model to non-developer users

Musculoskeletal model for prosthetic design improvement

- Help orthopaedic companies to quantify new designs on biomechanics parameters

  → **Orthopaedic companies**: need of collaborations between academic and industrial fields

Thank you

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