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Innovation that takes us there
-
how iterative prototyping revolutionizes para-rowing for GOLD

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PARA EQUIPMENT - The problem

The equipment is fixed within each Para class and not at all customized to the individual abilities, movement envelopes and parameters.

… so less than optimal in terms of performance and "fit", both in races and during training

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PARA EQUIPMENT - The solution

Step 1

Combining ***quantitative experiments*** to find a better master position (needs ***invention of new sensors and test rigs***)

Step 2

Followed by fast ***iterative improvements*** together with the athletes using ***Human-Centred Design (HCD)***, modern CAD and additive manufacturing technologies.

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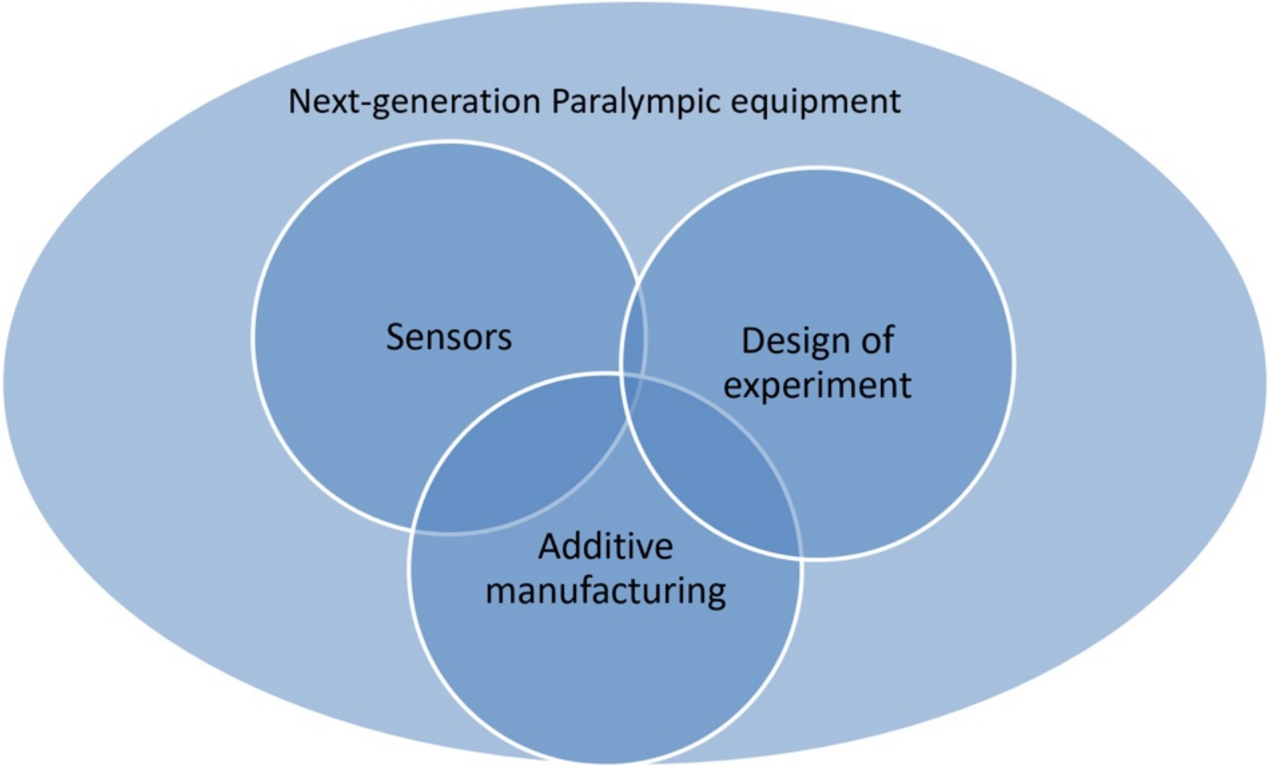
Ergo, NEW TOOLS



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PARA EQUIPMENT – Approach

1. **Observe and compare Para athletes to able bodied athletes with focus on movement envelope**

2. **Spot potential dimensions for improvement**

3. **Run fast prototypes and experiments**

4. **Create/Invent Experiment setup and necessary measurements and sensors**

5. **Run *quantitative controlled experiment***

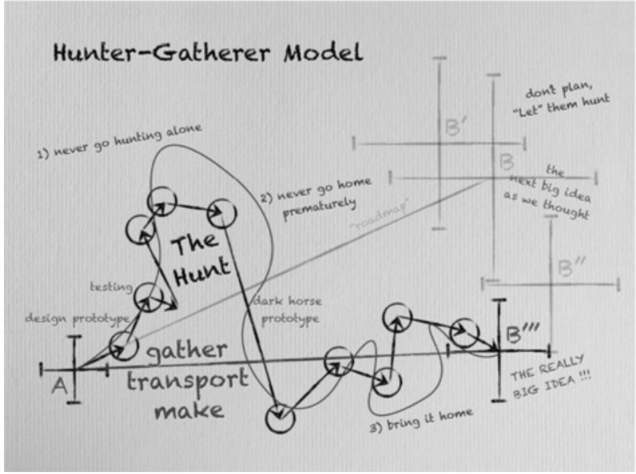
6. ***→ new master geometry***

7. **Run multiple *iterative improvement* rounds with athletes to customize the design (low end material)**

8. **Redesign in CAD, potential for topology optimization**

9. **Build high end version (3D printing of high-end material)**

10. ***→ athlete is performing better, can train more and has less injuries … might even be a bit happier and more motivated***



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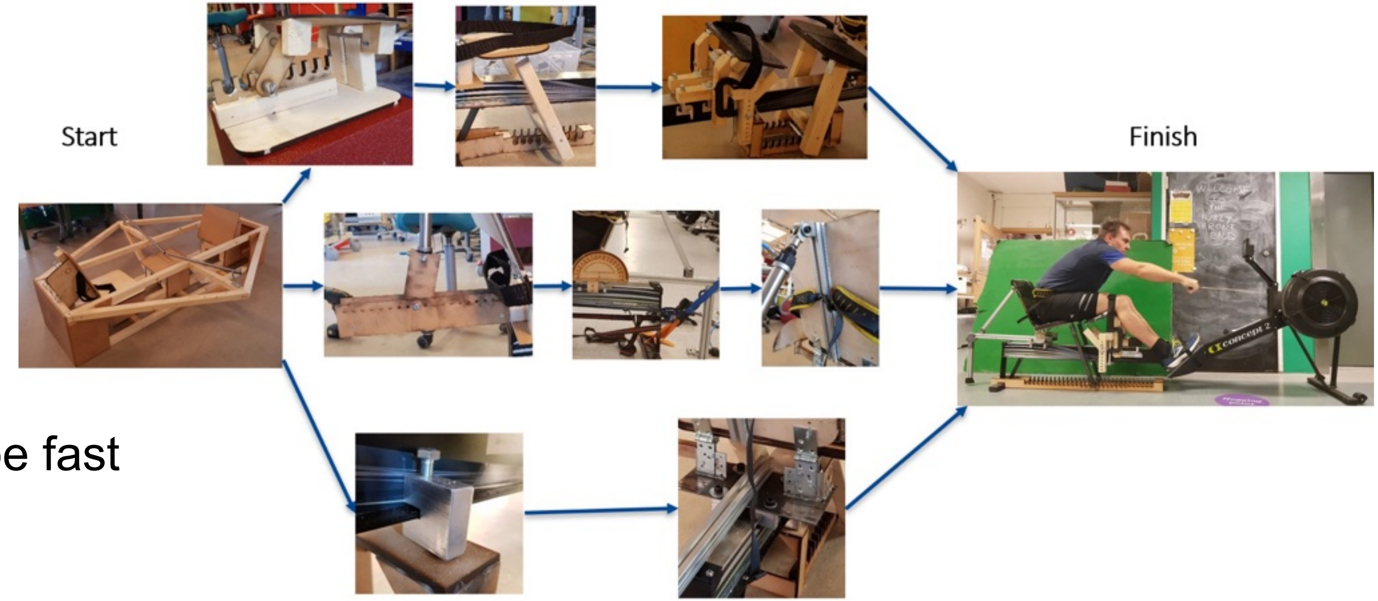
Prototyping, testing and iterating cost-effective into an optimal design

- Prototyping testing equipment
- Make iterations and generate ***learning***
- Prototypes should be fast and simple



[1] S. W. Eikevåg, A. Kvam, M. K. Bjølseth, J. F. Erichsen, and M. Steinert, "DESIGNING AN EXPERIMENT FOR EVALUATING SEATING POSITIONS IN PARALYMPIC ROWING," Proceedings of the Design Society: DESIGN Conference, vol. 1, pp. 2485–2494, May 2020, doi: 10.1017/dsd.2020.101.

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DESIGNING AN EXPERIMENT FOR EVALUATING SEATING POSITIONS IN PARALYMPIC ROWING

- Spot potential dimensions for improvement
- Generate adjustment possibilities able to create a performance map for each specific athlete

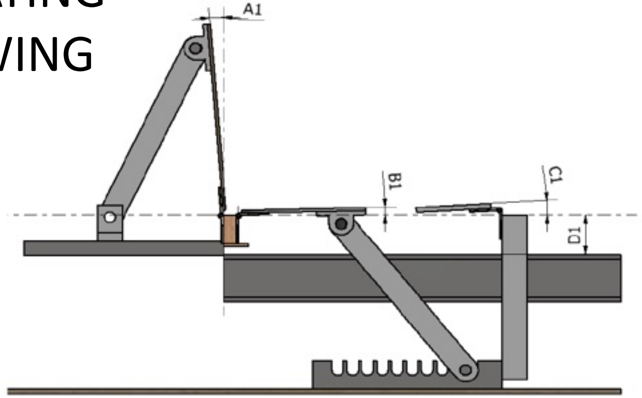
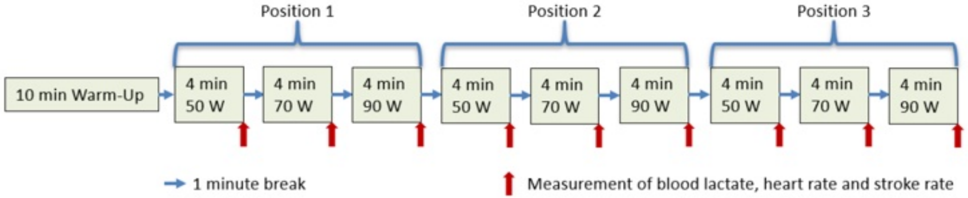
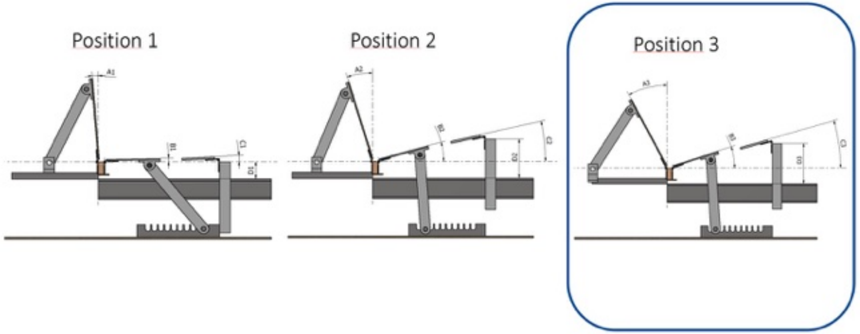


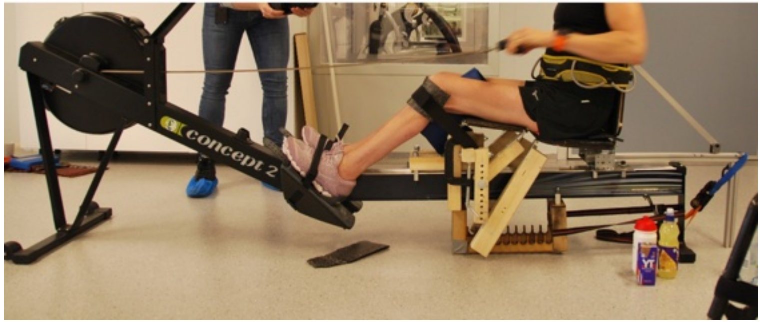
Figure 4. Position 1

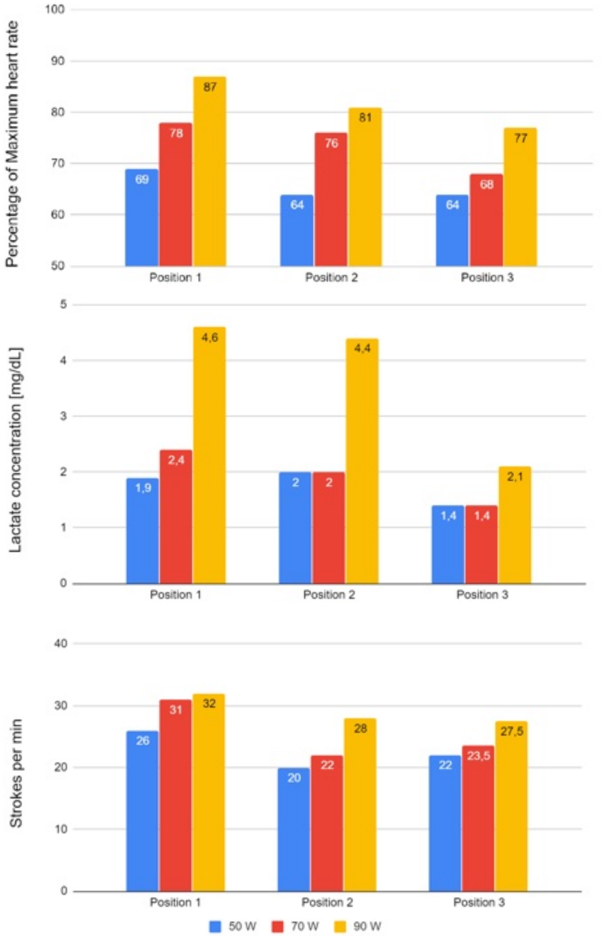


[1] S. W. Eikevåg, A. Kvam, M. K. Bjølseth, J. F. Erichsen, and M. Steinert, "DESIGNING AN EXPERIMENT FOR EVALUATING SEATING POSITIONS IN PARALYMPIC ROWING," Proceedings of the Design Society: DESIGN Conference, vol. 1, pp. 2485–2494, May 2020, doi: 10.1017/dsd.2020.101.

Experiment 1







[1] S. W. Eikevåg, A. Kvam, M. K. Bjølseth, J. F. Erichsen, and M. Steinert, "DESIGNING AN EXPERIMENT FOR EVALUATING SEATING POSITIONS IN PARALYMPIC ROWING," Proceedings of the Design Society: DESIGN Conference, vol. 1, pp. 2485–2494, May 2020, doi: 10.1017/dsd.2020.101.

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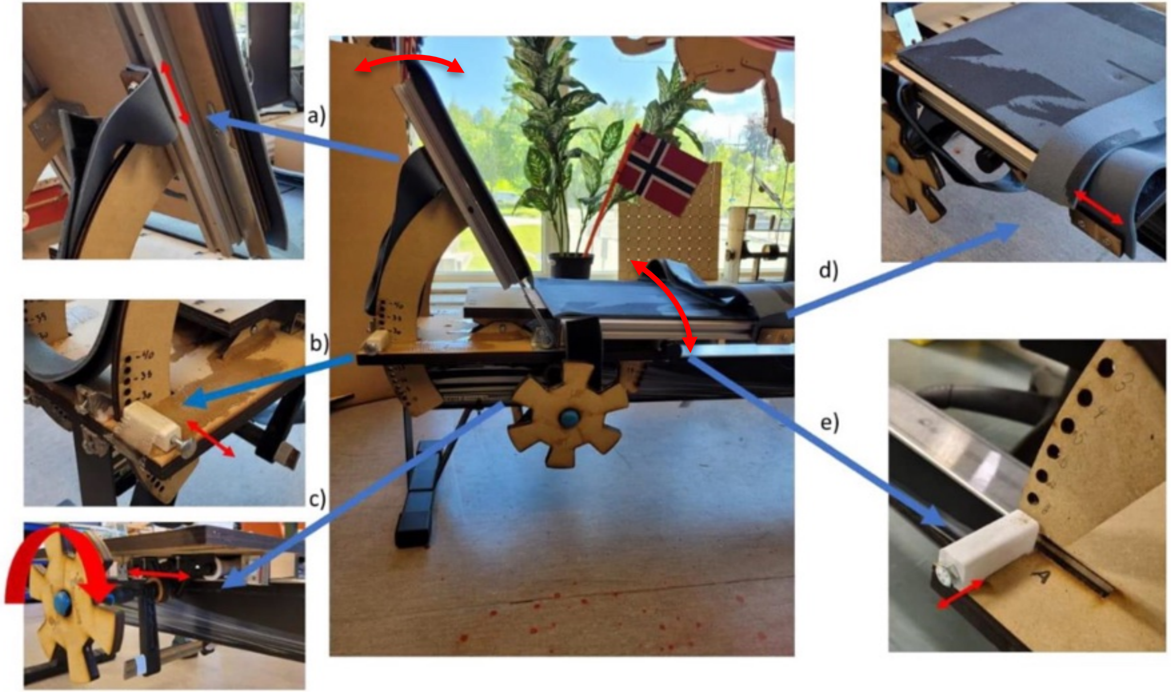

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Case Report: Adjusting Seat and Backrest Angle Improves Performance in an Elite Paralympic Rower

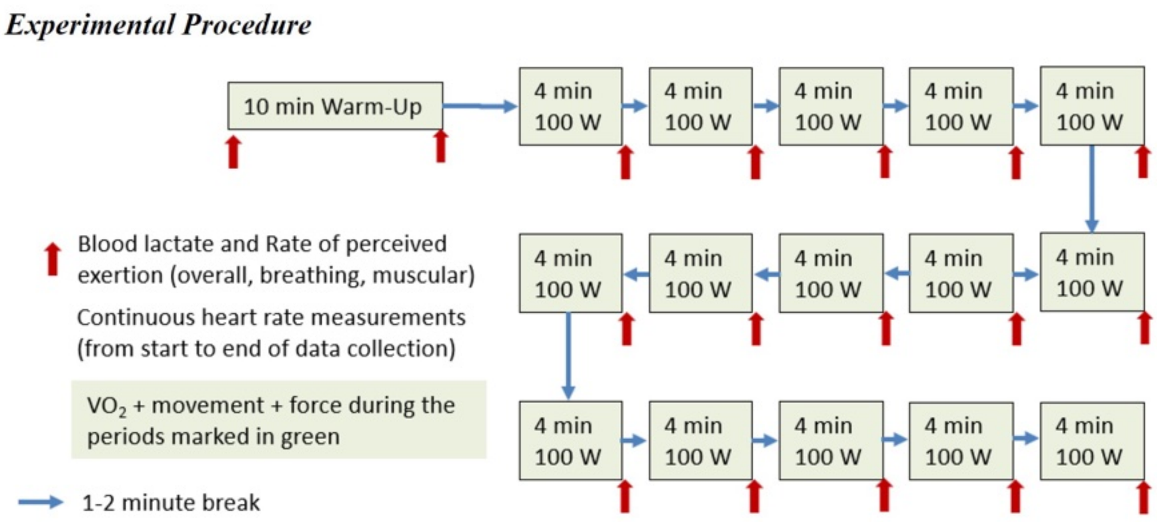
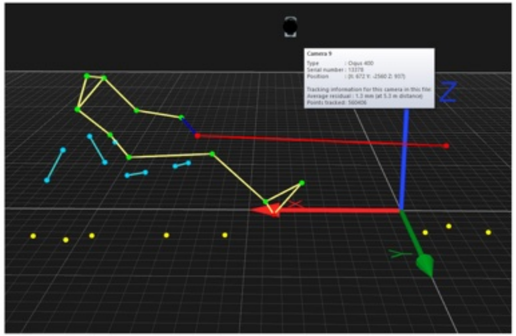
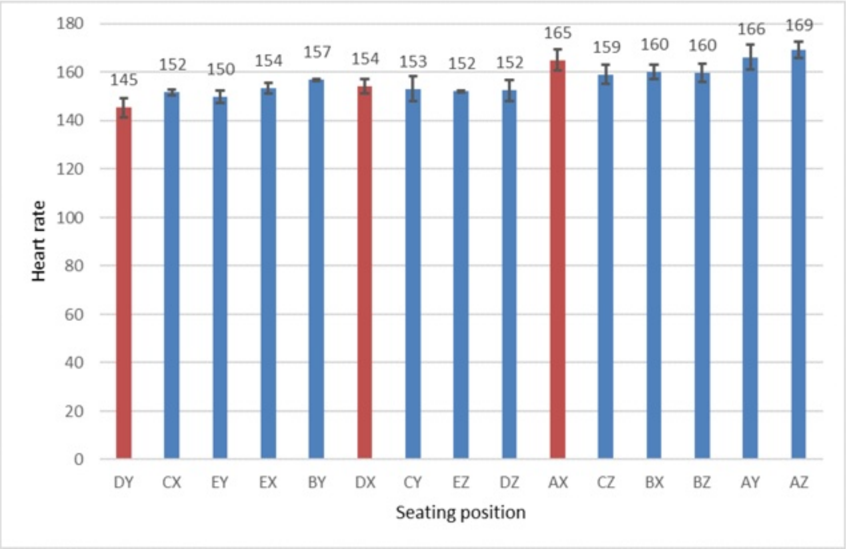


Figure 6. Experimental procedure for the first day of testing.



[3] A. C. Severin et al., “Case Report: Adjusting Seat and Backrest Angle Improves Performance in an Elite Paralympic Rower,” Front. Sports Act. Living, vol. 3, 2021, doi: 10.3389/fspor.2021.625656.



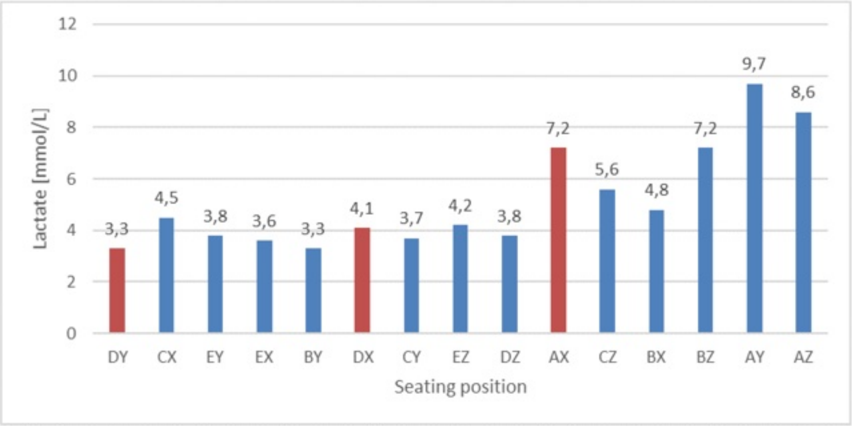


Figure 19: Lactate, measured in mmol/L. The positions further investigated are highlighted

Table 8: Physical strain data noted by the athlete after low-power tests, on the Borg scale, from 6 to 20. The positions further investigated are highlighted in yellow.

	DY	CX	EY	EX	BY	DX	CY	EZ	DZ	AX	CZ	BX	BZ	AY	AZ
Muscular	10	11	10	10	13	12	12	13	13	14	13	13	13	15	14
Ventilation	12	10	10	10	11	12	12	12	11	14	11	11	10	14	11
General	11	11	10	10	12	12	12	12	12	14	12	12	12	15	12

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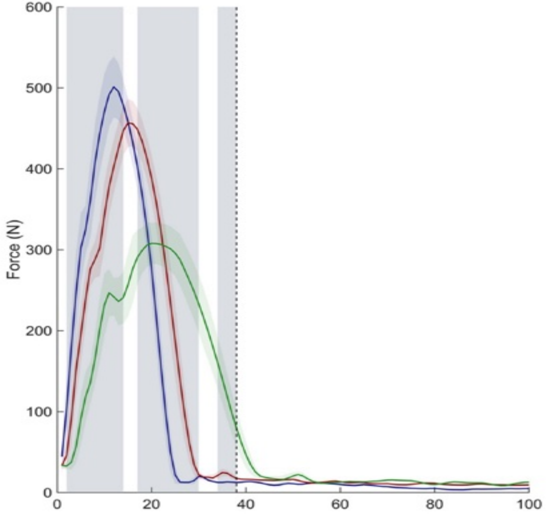
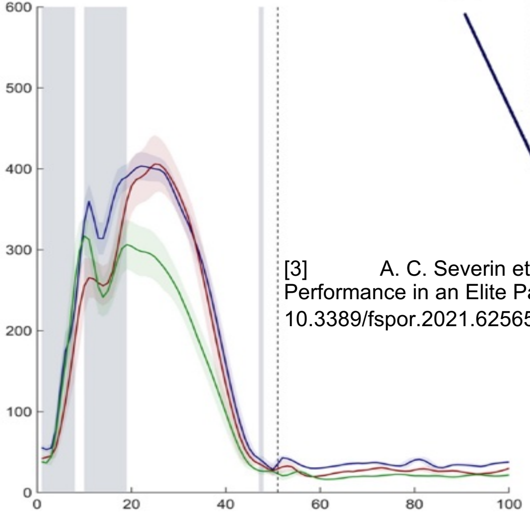
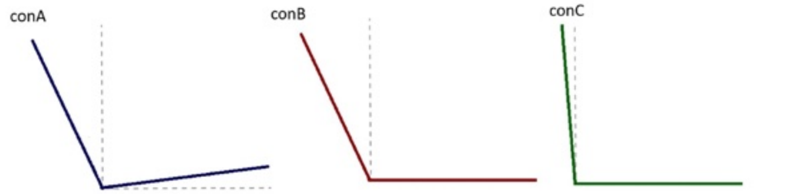
SUBMAX



MAX





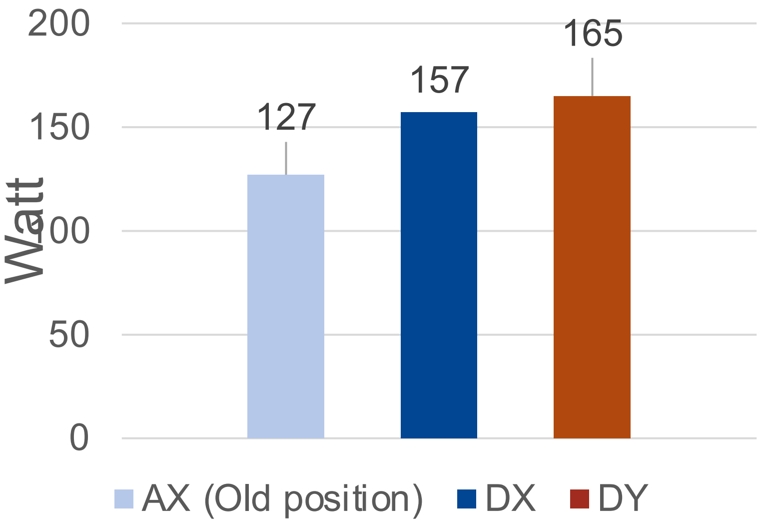
[3] A. C. Severin et al., "Case Report: Adjusting Seat and Backrest Angle Improves Performance in an Elite Paralympic Rower," Front. Sports Act. Living, vol. 3, 2021, doi: 10.3389/fspor.2021.625656.

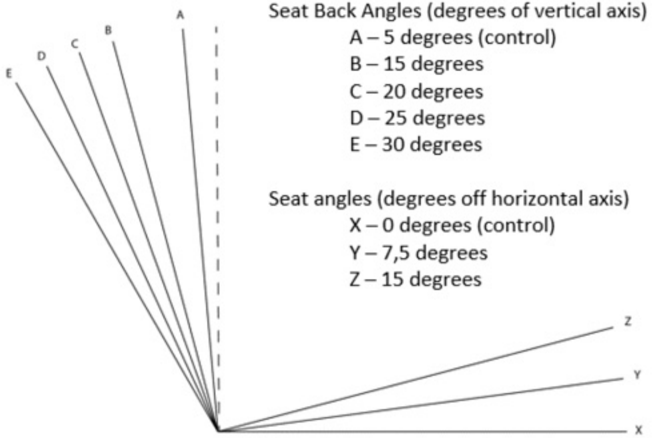
Table 6: Physical strain data noted by the athlete after high-power tests, on the Borg scale from 6 to 20

	DY			DX			AX		
Target Power	80 W	100 W	All-out	80 W	100 W	All-out	80 W	100 W	All-out
Muscular	9	12	20	11	13	20	14	15	19
Ventilation	9	11	19	9	11	18	11	12	17
General	9	11	20	10	12	19	12	14	19

Experiment 2

- Sub-max 100W 4min testing of 15 positions
- All-out test of Old position, and top two positions from all-out testing





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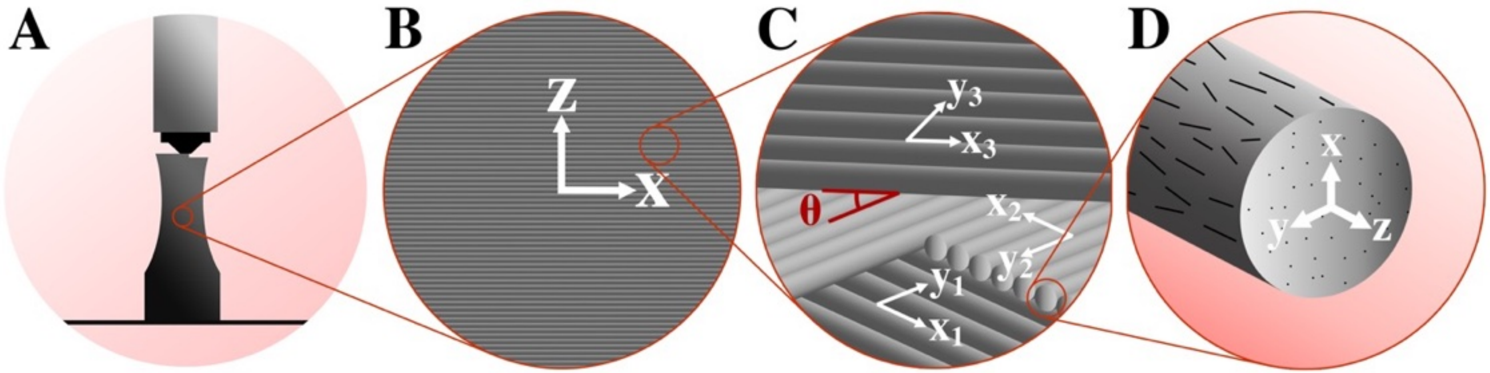
Anisotropic properties in fused filament fabrication based on current literature



(A) Hardware selection and processing.
(B) Interlayer bonding.
(C) Raster angle and in layer thermal fusion.
(D) Fiber orientation by acceleration, nozzle path and randomness

Progress in Additive Manufacturing (2022) 7:1111–1122
https://doi.org/10.1007/s40964-022-00285-8

FULL RESEARCH ARTICLE

Comprehensive characterization of mechanical and physical properties of PLA structures printed by FFF-3D-printing process in different directions

Giulia Morettini[1] · Massimiliano Palmieri[1] · Lorenzo Capponi[1] · Luca Landi[1]

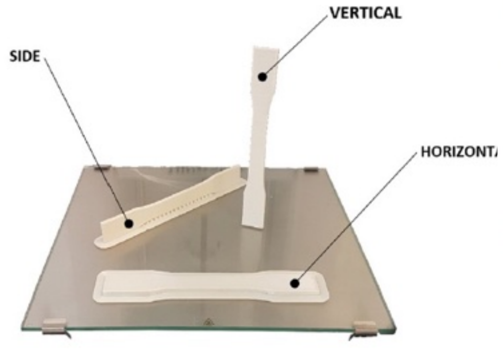
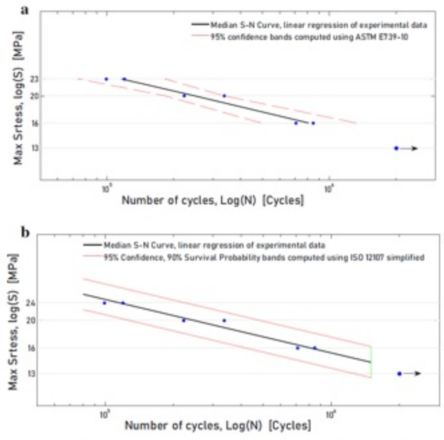
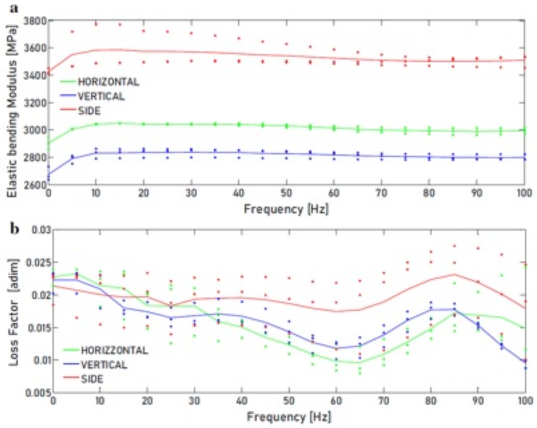


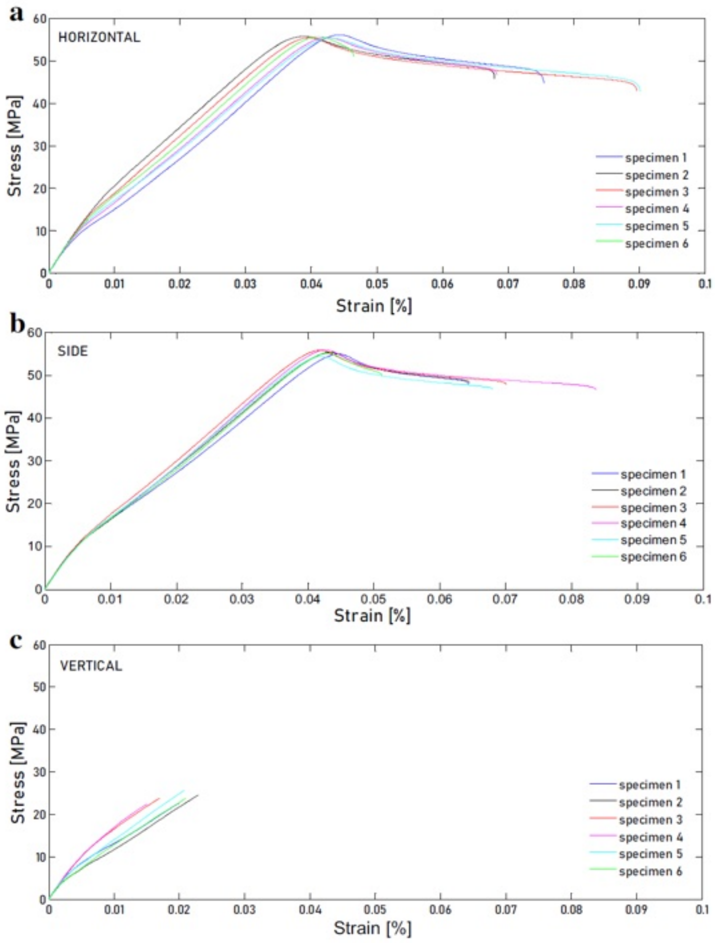
Fig. 2 Real specimens (for fatigue or tensile test) on the print plate



5 Results of the fatigue tests. a 95% confidence bands computed using ASTM E739-10. b 95% confidence, 90% survival probability bands puted using ISO 12107 simplified



3-points bending results of DMA test



Stress–strain curves results for the three build directions for the 18 tensile test specimens

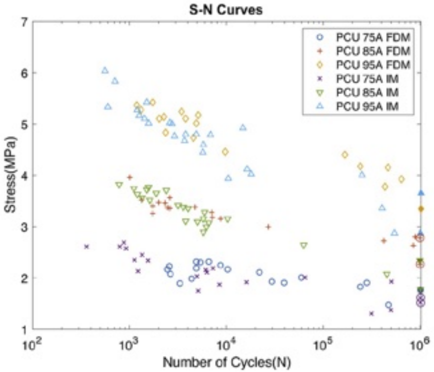
Contents lists available at ScienceDirect

Additive Manufacturing

journal homepage: www.elsevier.com/locate/addma

A review of the fatigue behavior of 3D printed polymers

Lauren Safai*, Juan Sebastian Cuellar, Gerwin Smit, Amir A. Zadpoor



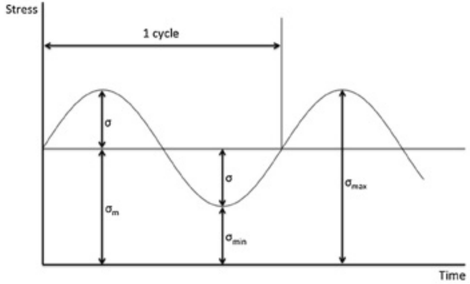


Fig. 1. Nomenclature that describes testing parameters in constant amplitude loading.

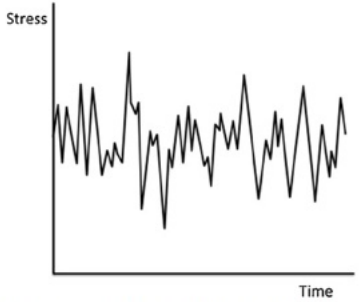


Fig. 2. An example of a general variable amplitude loading.

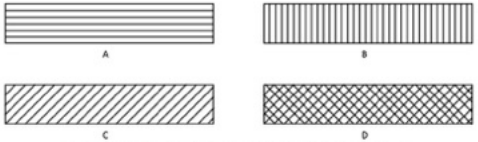


Fig. 4. Four different raster orientations of A) 0°, B) 90°, C) 45°, and D) 45°/45°.

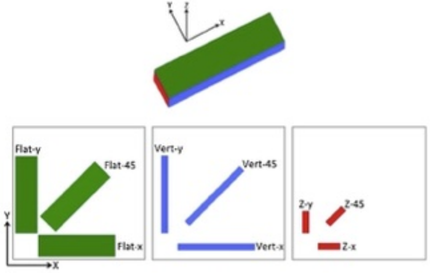
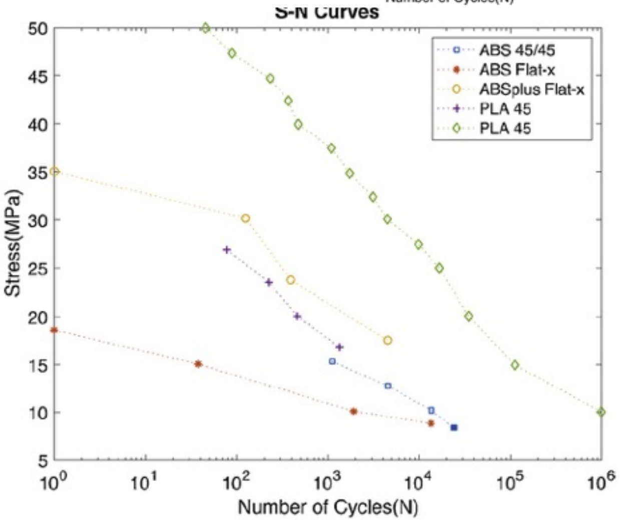
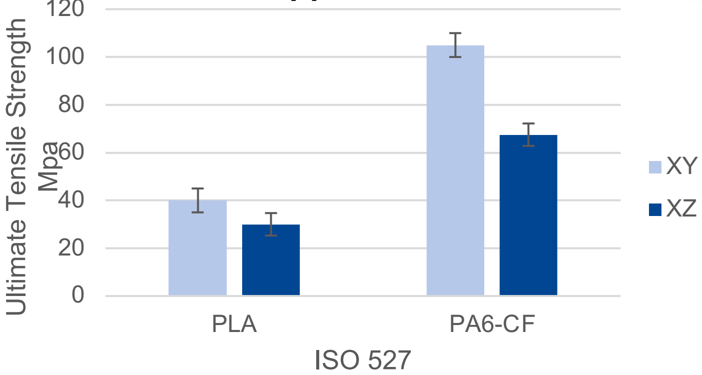


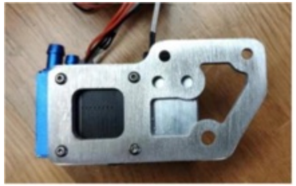
Fig. 5. An arbitrary geometry that shows the notation of the nine different printing orientations on an XYZ stage.



[1] Das et. Al. 2020



[5] PolyMide PA6-CF



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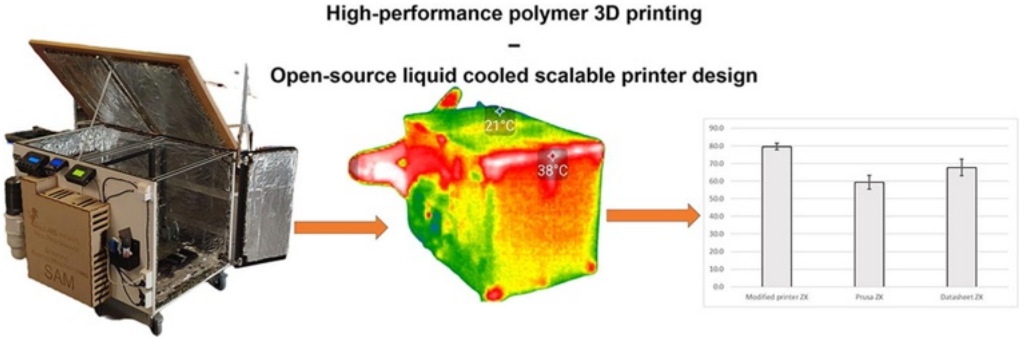
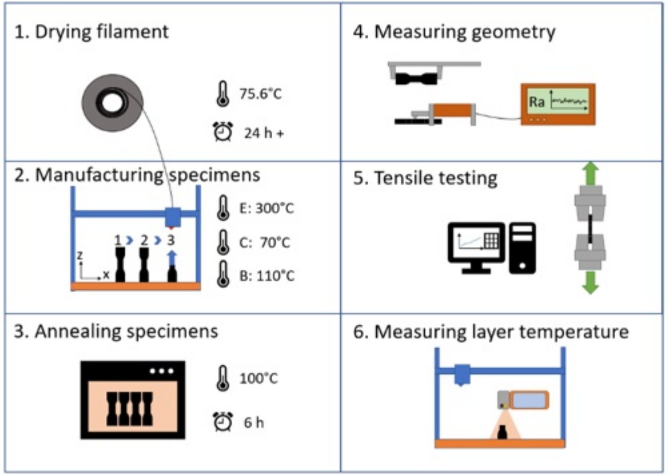
High-performance polymer 3D printing – Open-source liquid cooled scalable printer design



IKEA cabinets for a better tomorrow!

Applied sciences: Thermal Layer Design in Fused Filament Fabrication



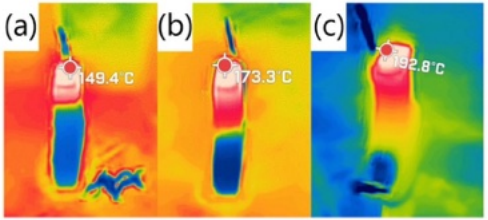
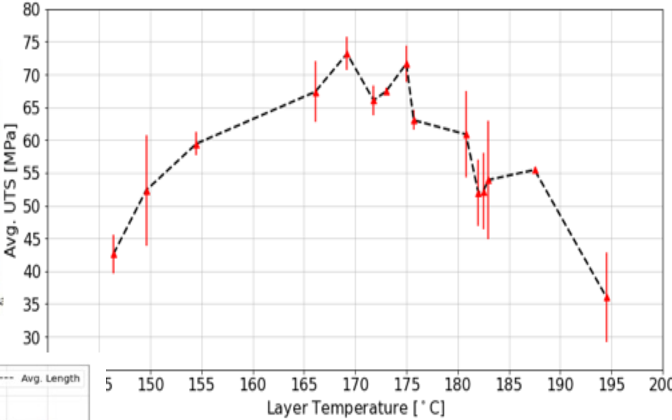
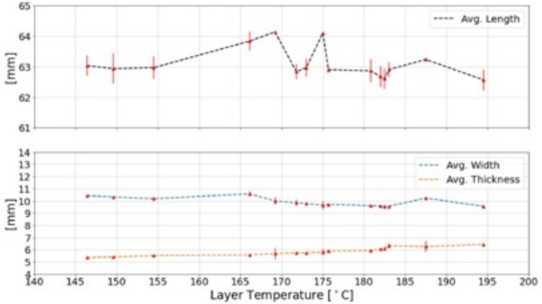
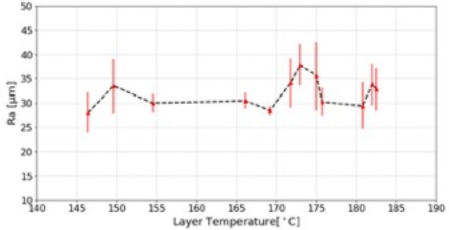
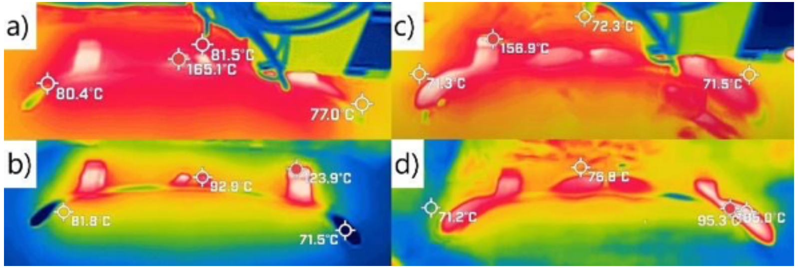


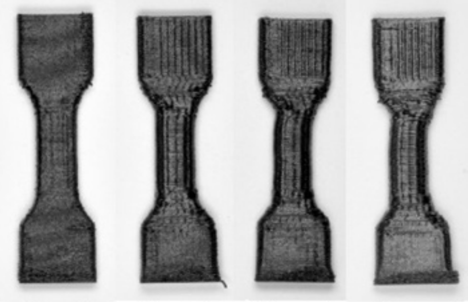
Figure 10. Thermal images of the layer temperature of specimens printed a (b) 10 mm/s, and (c) 30 mm/s.



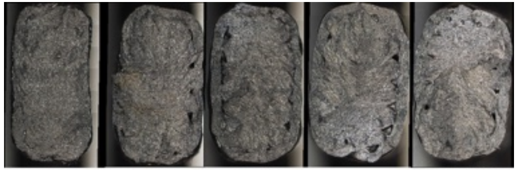








6 mm/s	14 mm/s	20 mm/s	30 mm/s
154.5°C	180.8°C	183.3	194.5°C



146.4 °C · 169.2 °C · 175.7 °C · 182.0 °C · 183.0 °C

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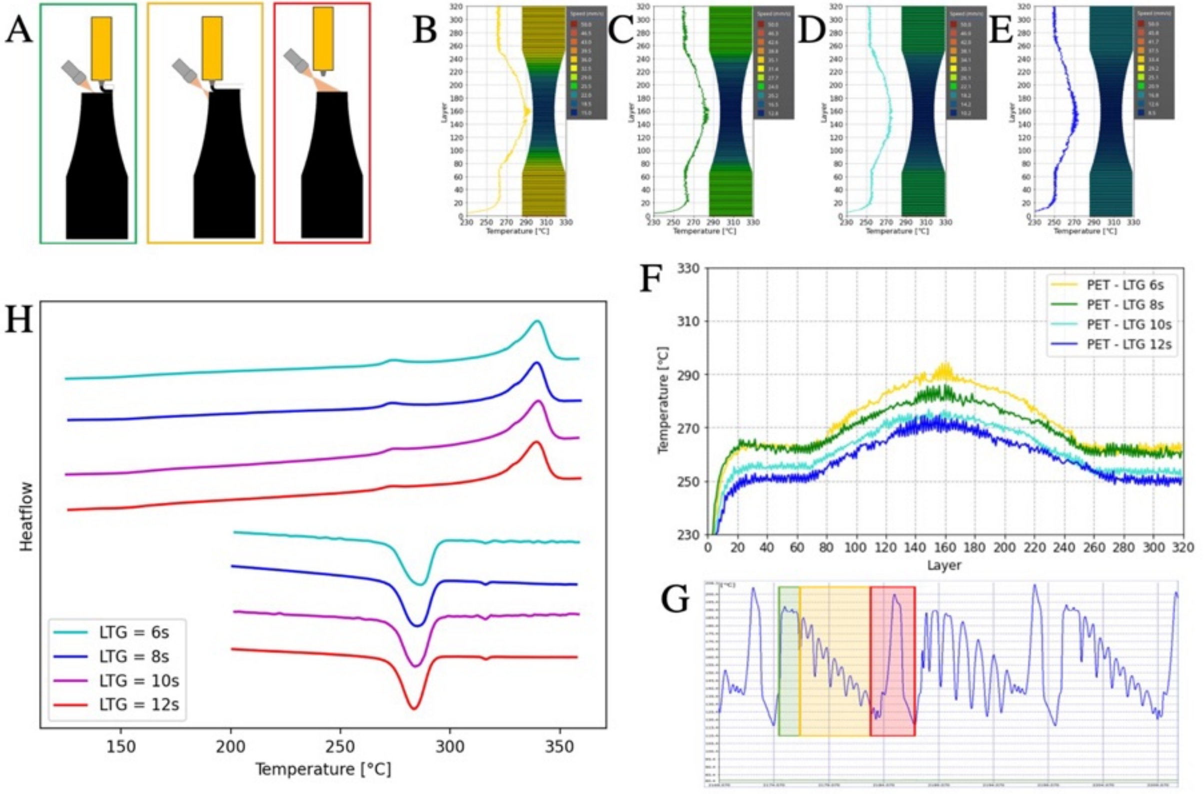
LTG Layer temperature and correlating material properties from differential scanning calorimeter.

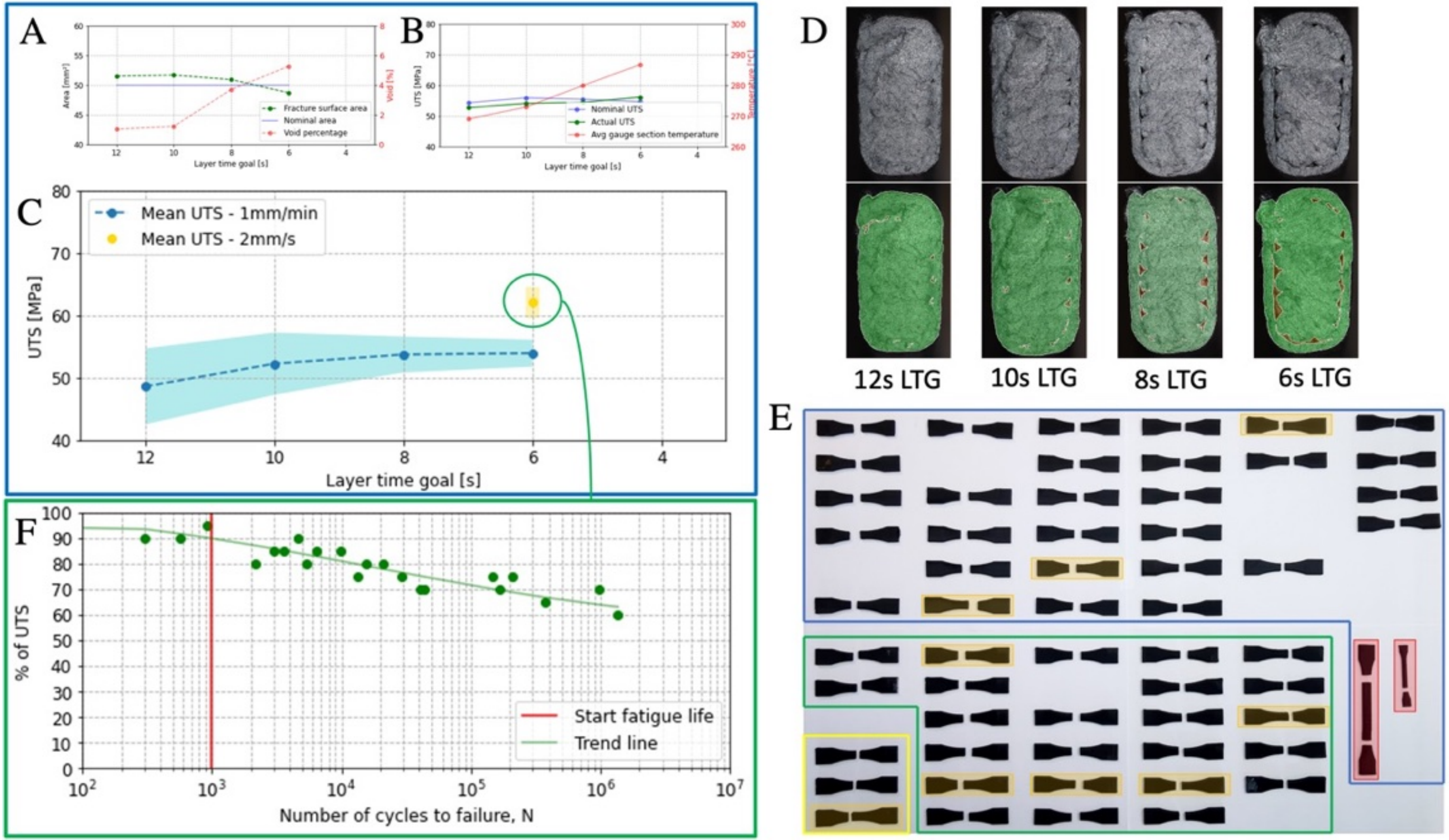
Table 1. Key values extracted from the DSC analysis of different LTG samples.

LTG [s]	ΔH_m [J/g]	T_g [°C]	T_m [°C]	T_{hc} [°C]
6	33.8	163.7	339.6	286.5
8	31.9	162.1	339.3	285.1
10	37.5	161.4	339.9	284.0
12	34.4	158.9	339.2	283.4

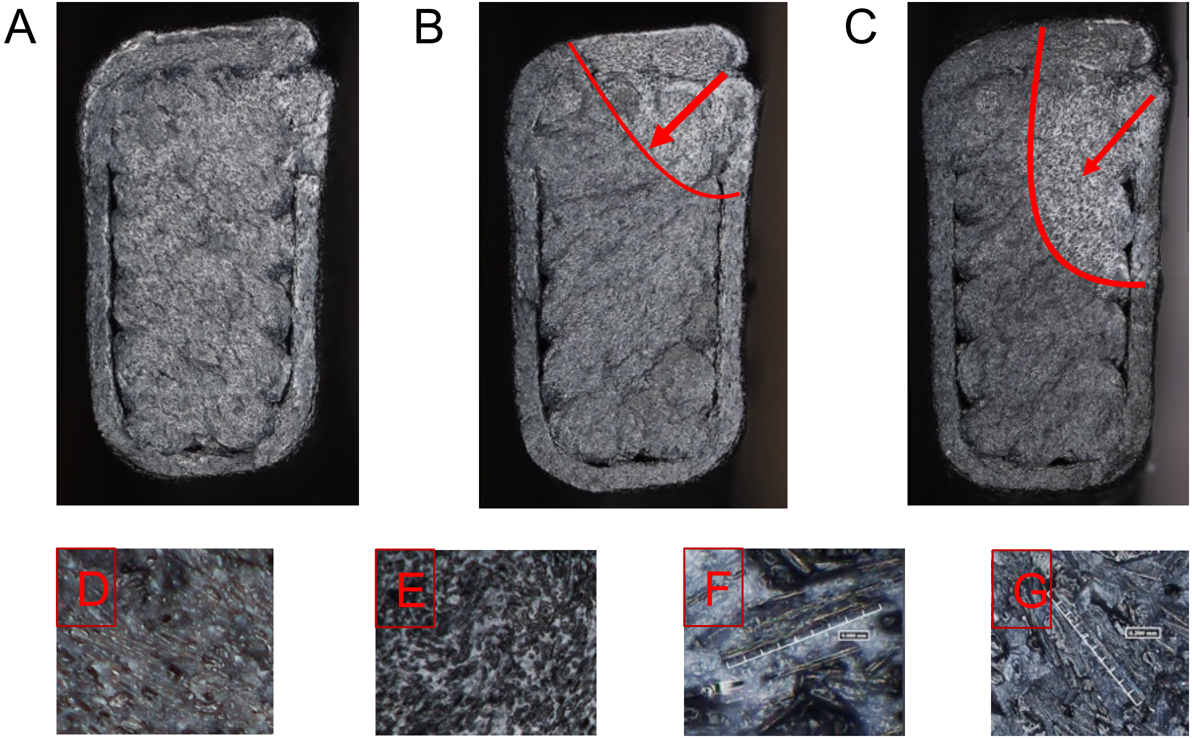


(A) Filtered layer temperatures when dispositioning new material at different layer time goals. **(B to E)** layer temperatures of the different LTG specimens though out the geometry. **(F to G)** Temperature readings at different nozzle positions and applied filter. Green area provides the temperatures presented in (A). **(H)** Heat flow through material acquired from differential scanning calorimetry (DSC) analysis. The top four graphs depicting the heating run, and the bottom four depicting the cooling run.

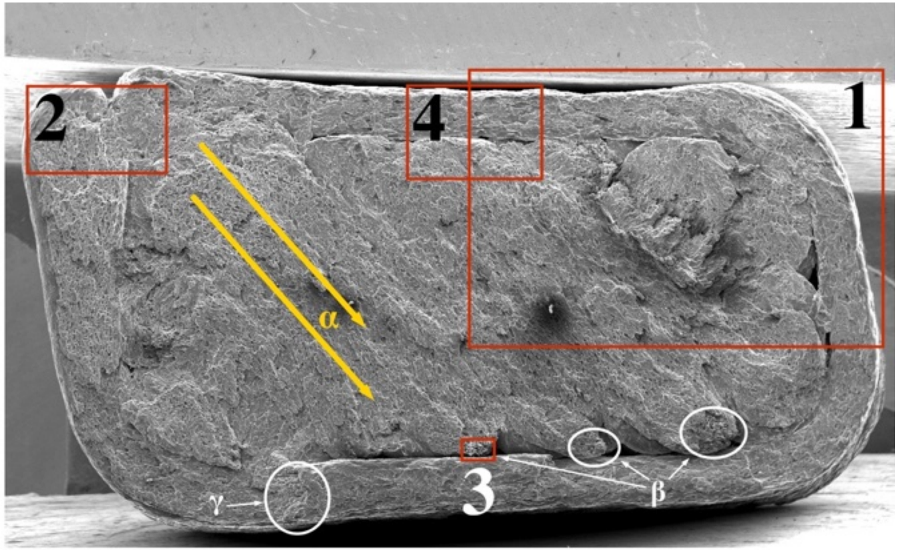
PEEK-CF



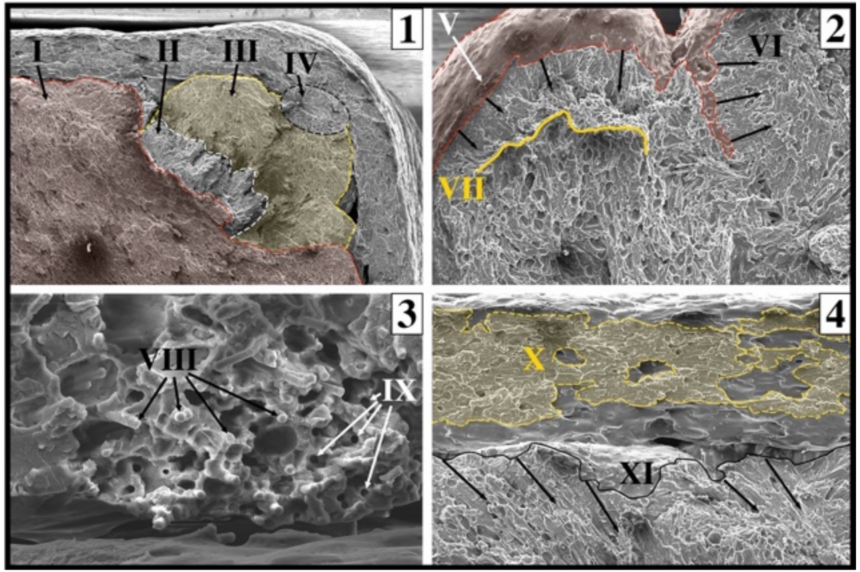
A
Fracture surface area
Nominal area
Void percentage
Area [mm²]
Void [%]
Layer time goal [s]
B
Nominal UTS
Actual UTS
Avg gauge section temperature
UTS [MPa]
Temperature [°C]
Layer time goal [s]
C
Mean UTS - 1mm/min
Mean UTS - 2mm/s
UTS [MPa]
Layer time goal [s]
D
12s LTG
10s LTG
8s LTG
6s LTG
E
F
Start fatigue life
Trend line
% of UTS
Number of cycles to failure, N


A
B
C
D
E
F
G

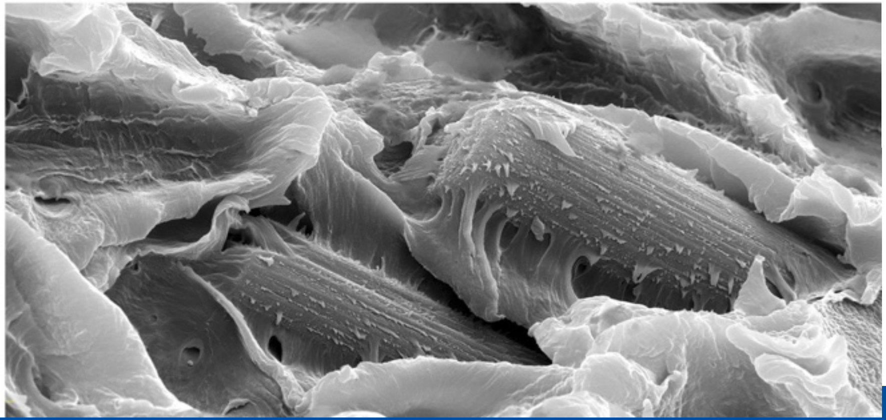
A

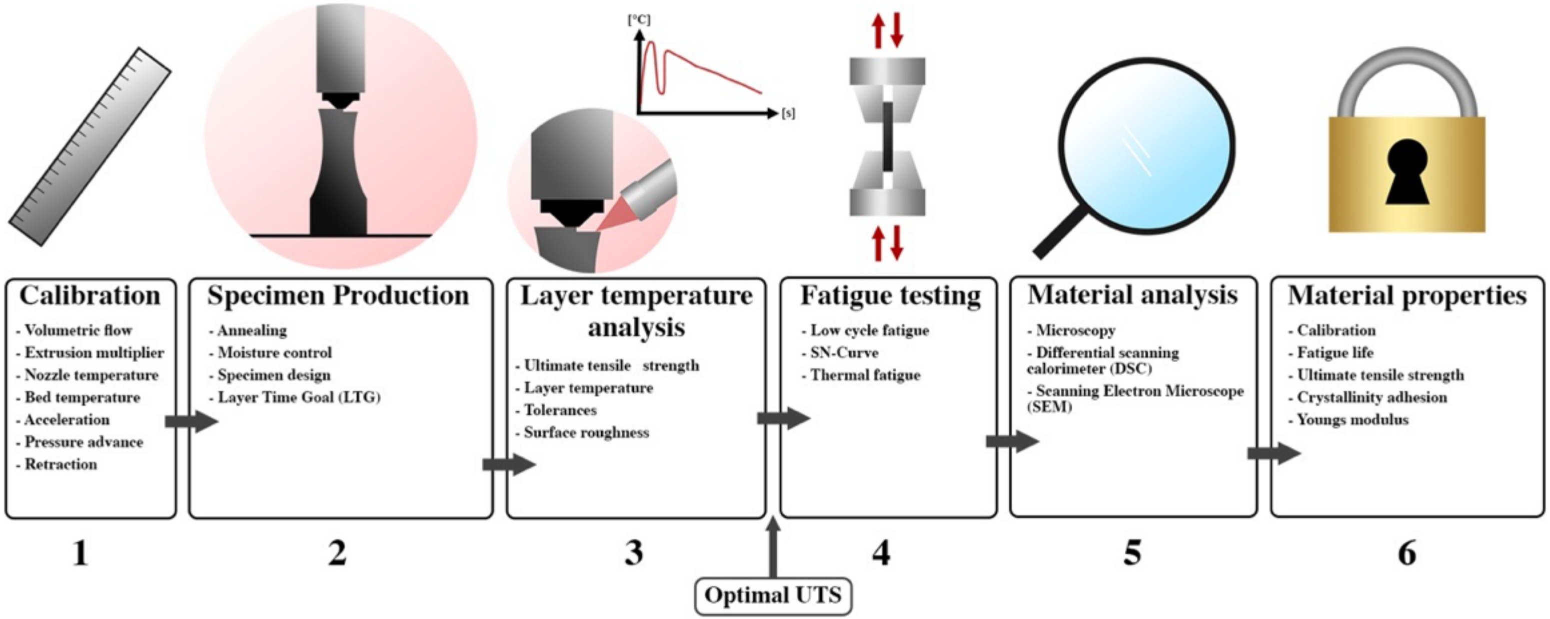


B



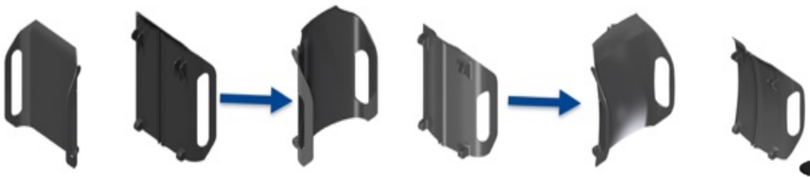
C

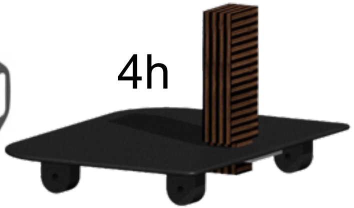




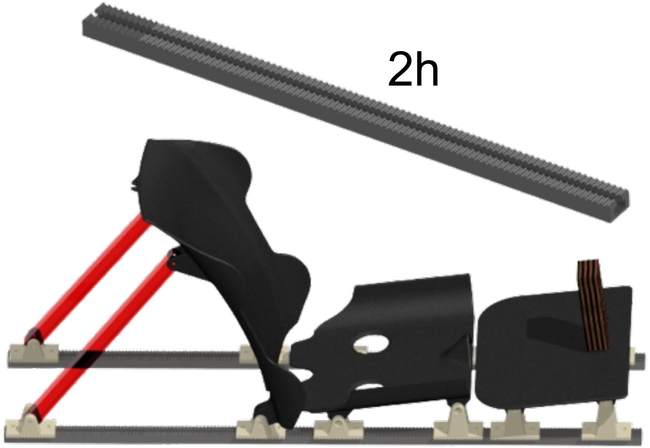
[°C]
[s]
Calibration
- Volumetric flow
- Extrusion multiplier
- Nozzle temperature
- Bed temperature
- Acceleration
- Pressure advance
- Retraction
1
Specimen Production
- Annealing
- Moisture control
- Specimen design
- Layer Time Goal (LTG)
2
Layer temperature analysis
- Ultimate tensile strength
- Layer temperature
- Tolerances
- Surface roughness
3
Optimal UTS
Fatigue testing
- Low cycle fatigue
- SN-Curve
- Thermal fatigue
4
Material analysis
- Microscopy
- Differential scanning calorimeter (DSC)
- Scanning Electron Microscope (SEM)
5
Material properties
- Calibration
- Fatigue life
- Ultimate tensile strength
- Crystallinity adhesion
- Youngs modulus
6

Prototyping for athlete individual fitment, support and design for performance - Iterations by 3D printing





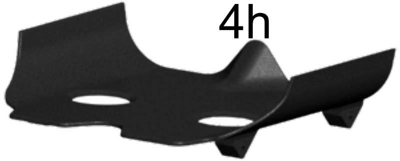
4h



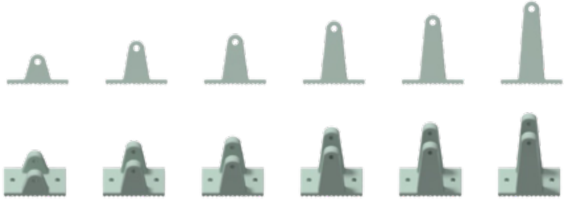
2h

- No geometric restrictions compared to traditional production methods
- Maximum 5 hours lead time per component
- Equipment tailored per individual athlete
- Possibilities for 1) implemented 3D scanning 2) topology optimalization 3) generative design

5h



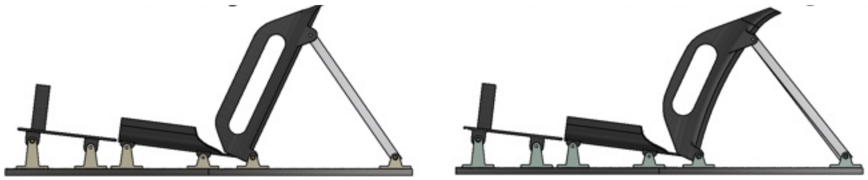
4h



12 minutes each

[6] Sindre .W. Eikevåg, Martin Steinert., PR1 indoor rowing world record and 3D printing of high-performance polymers – Prototyping and customizing high-end Paralympic equipment., VISTA 2021 Conference

And make many many more prototypes



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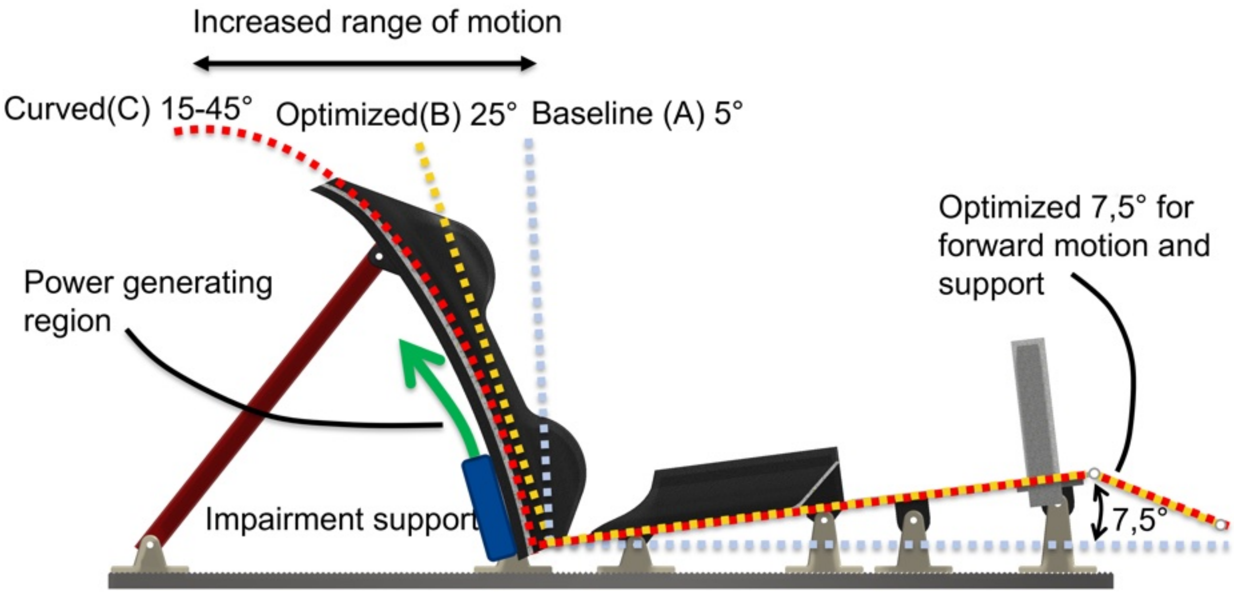

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PR1 indoor rowing world record and 3D printing of high-performance polymers- Prototyping and customizing high-end Paralympic equipment

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Introduction

In Paralympic sports at the highest-level, equipment design is crucial [1]. Prototyping and trails, modifications and, at best, customizations are often necessary to allow for individual peak performance/injury prevention. Today's materials of choice such as vacuum assisted resin infusion of carbon fiber or CNC milled aluminum usually do not allow for intensive prototyping. Recently new high-performance polymers [2] have been made available for 3D printing using fused filament fabrication (FFF). This technology allows for fast prototyping, testing, redesign, and customized high-end manufacturing together with the athlete to build truly fitting equipment, that cater each individual case.

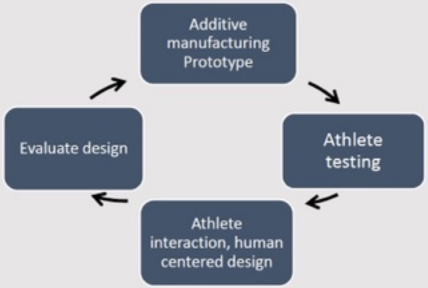


Figure 2 - Product development Iteration cycle

Method

Equipment design for a world class Paralympic rower was developed. First designed in CAD (Computer Aided Design) and prototyped using FFF, the athlete could test and evaluate multiple setups, geometries, and body interface iteratively. When working with top level athletes time is critical, as access to the athlete is limited. Long production times thus often prevent iterative prototyping. By changing to FFF, lead-times can be drastically decreased, in this case to as short as 5h allowing for significantly more iterations, learning, and consequently performance and fit. The extended prototyping and customization cycle of the equipment design has had a major impact on the Paralympic athlete's performance.

The FFF technology enables additional functions such as 3D scanning of human interface into components, and topology optimization for weight reduction. Using cheap and fast prototypes in PLA with approximately 30MPa tensile strength and high-performance **polymers PA-CF with 105MPa X-Y material strength and 67,7MPa X-Z layer adhesion with a density of 1,17g/cm³** for final production created the best combination [2]. PA-CF can not only rival traditional production materials due to its low weight and strength but allows for novel designs with no geometric restrictions.

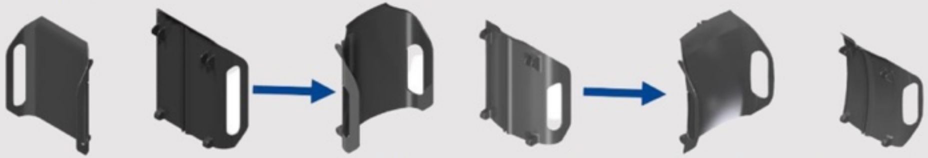
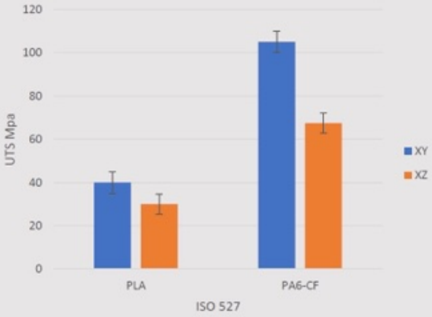


Figure 1 – A selection of different iterations cycles of 3D printed components. The design was changed after results from physical testing and feedback from the coach and athlete.

Result

During testing, the final design developed in collaboration with a top-level athlete increased performance to 186W by 12,7%, with 972m distance at 4 minutes all-out [1], before being used at the Paralympic indoor rowing world championship. The design had radical changed during iterations and is not easily commercially available, it did however assist the athlete in achieving **a new women's PR1 2000m indoor world record of 8.18,5.**

Figure 3 - CAD model of the prototype, iterated by 3D printing high performance polymers



[5] PolyMide PA6-CF

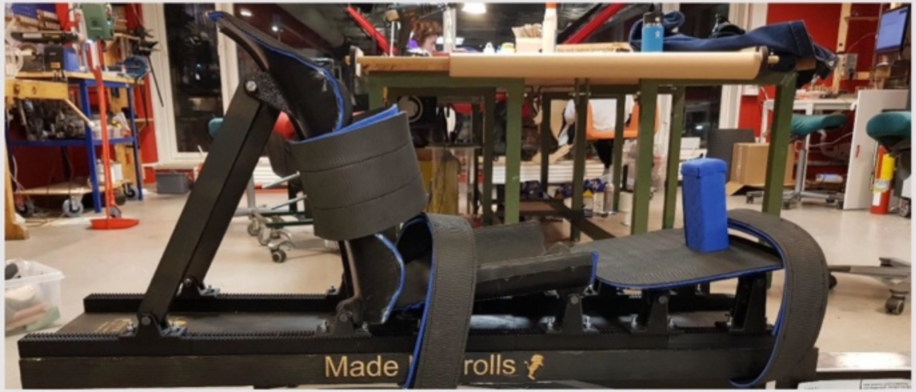


Figure 5 - 3D printed PR1 seating assembly used in the world indoor rowing championship.

References:

1] Sindre W. Eikevåg, Jørgen Falck Erichsen ,Martin Steinert., Sports equipment design impact on athlete performance – The PR1 Paralympic women's indoor rowing world record., Under review ICEA2022

2] Eikevåg, S.W., Kvam, A., Bjølseth, M.K., Erichsen, J.F., Steinert, M., 2020. DESIGNING AN EXPERIMENT FOR EVALUATING SEATING POSITIONS IN PARALYMPIC ROWING. Proceedings of the Design Society: DESIGN Conference 1, 2485–2494. https://doi.org/10.1017/dsd.2020.101

3] Severin, A.C., Danielsen, J., Falck Erichsen, J., Wold Eikevåg, S., Steinert, M., Ettema, G., Baumgart, J.K., 2021. Case Report: Adjusting Seat and Backrest Angle Improves Performance in an Elite Paralympic Rower. Front. Sports Act. Living 3. https://doi.org/10.3389/fspor.2021.625656

4] "PolyMideTM PA6-CF," Polymaker EU, 2020. https://eu.polymaker.com/product/polymide-pa6-cf/ (accessed Nov. 12, 2020).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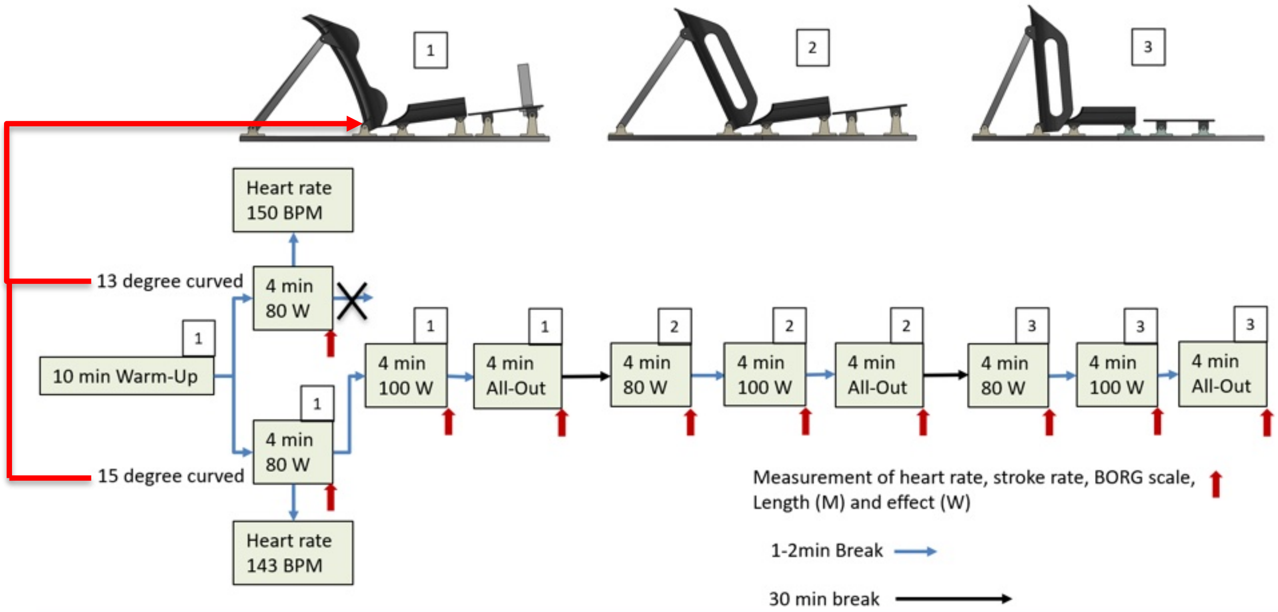

		Curved seatback				Straight seatback 25 degrees				Original seating position		
	Warm Up	80W 13deg	80W 15de	100W	All-Out		80W	100W	All-Out	80W	100W	All-Out
Ventriculert	na	8	8	12	19		8	12	18	10	15	17
Musculert	na	8	8	15	20		10	14	19	10	15	19
Generelt	na	8	8	14	20		9	13	19	10	15	18
Heart rate	139	150	143	157	184		153	166	189	159	170	186
Stroke rate	na	26	28	29	42		28	33	47	35	41	56
Watt	65	80	80	100	**186**		82	100	**165**	81	98	**128**
Length	na	738	735	791	972		741	791	934	736	786	858

[7] Sindre W. Eikevåg, Jørgen Falck Erichsen ,Martin Steinert., Sports equipment design impact on athlete performance – The PR1 Paralympic women's indoor rowing world record., ICEA2022

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Old seating position

All-out 4 minutes:

- 128 Watt
- 858 Meters
- 56 Stroke rate

[7] Sindre W. Eikevåg, Jørgen Falck Erichsen ,Martin Steinert., Sports equipment design impact on athlete performance – The PR1 Paralympic women's indoor rowing world record., ICEA2022

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Optimal flat seatback

All-out 4 minutes:

- 165 Watt
- 934 Meters
- 47 Stroke rate

[7] Sindre W. Eikevåg, Jørgen Falck Erichsen ,Martin Steinert., Sports equipment design impact on athlete performance – The PR1 Paralympic women's indoor rowing world record., ICEA2022

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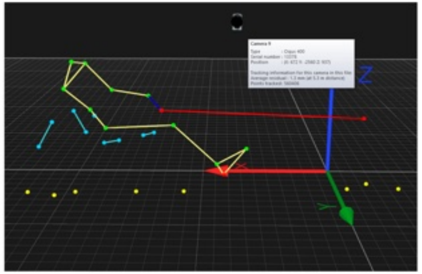
Curved seatback

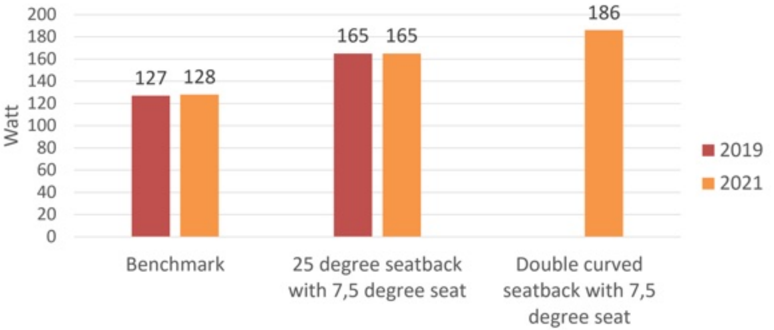
All-out 4 minutes:

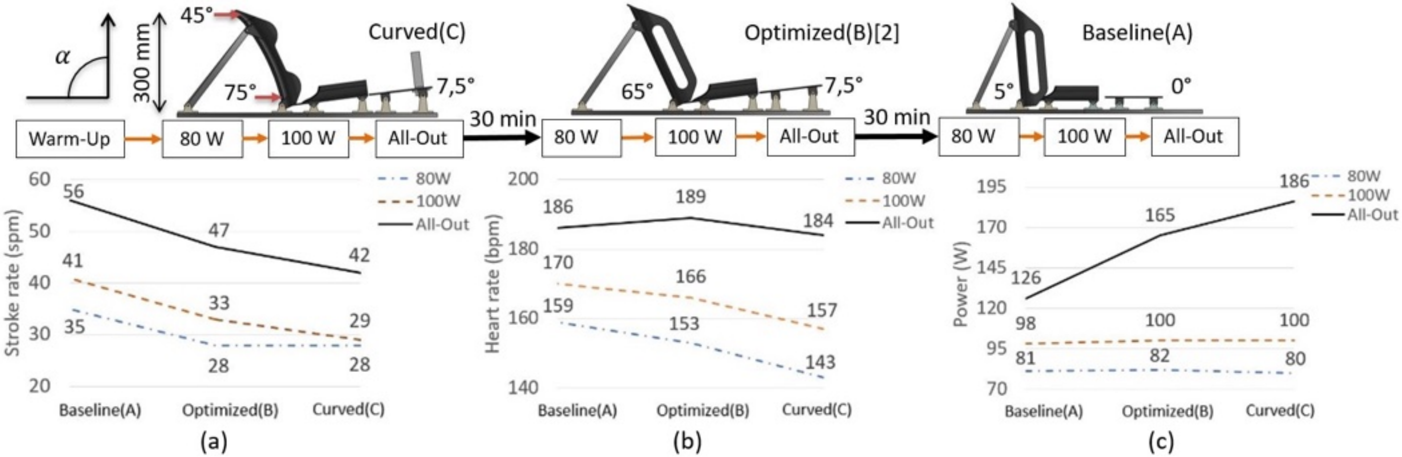
- 186 Watt
- 972 Meters
- 42 Stroke rate

[7] Sindre W. Eikevåg, Jørgen Falck Erichsen ,Martin Steinert., Sports equipment design impact on athlete performance – The PR1 Paralympic women's indoor rowing world record., ICEA2022

Equipment impact on athlete performance – The results after understanding the athlete







[7] Sindre W. Eikevåg, Jørgen Falck Erichsen ,Martin Steinert., Sports equipment design impact on athlete performance – The PR1 Paralympic women's indoor rowing world record., ICEA2022

Engineering design for Paralympics success – Research results

- Increased athlete performance
- Fun and motivating
- Improved technique
- move in a biomechanics "safer" as well as a more efficient and effective way
- Decreased amount of injury
- Increased training capacity and fitness
- HCD Paralympic setup & performance can not be generalized

Photo: Torstein Bøe / NTB

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IDRETTSTEKNOLOGI

Optimalt: – Så fort NTNU publiserer det vi har gjort frem til nå, tror jeg veldig mange internasjonalt vil rette seg etter det vi har gjort. Vi har svært gode resultater som er underbygget av solid testing og sterke tall. Metodikken vi har brukt for å finne frem til optimal sittestilling kan overføres til mange idretter, så jeg håper arbeidet vi har gjort kan danne grunnlaget for en standardprosedyre for uttesting av utstyr, sier Birgit Skarstein. FOTO: SVERRE CHR. JARILD

Effekten økte fra 165 til **186 watt** med kurvet ryggstøtte

Når Birgit Skarstein ror for Paralympics-gull i Tokyo denne uken, er det ingeniører ved NTNU som er ekstra spente på om forskningen deres vil gi medalje.

▸▸▸

Etter over 100 prototyper skal de få svar på om forskningen er

GULL VERDT

THOU SHALL PROTOTYPE