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Title: *Impact Strength Testing of Customized 3D-Printed Guards Made with Various Printing Methods and Materials*

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A previous study entitled *Impact Strength Testing of Customized 3D-Printed Guards* investigated the impact strength of *XO Armor* custom shoulder guards printed via fused deposition modeling (FDM) of polylactic acid (PLA). The study subjected three guards (1. 3mm thick with no padding; 2. 3mm thick with no padding and printing interruption; 3. 3mm thick with 3mm EVA foam padding) to repeated impacts with a weighted football helmet and hypothesized that each would break on or before the tenth impact. The interrupted guard broke on the tenth impact. The other two guards withstood ten impacts without breaking. The EVA-padded guard withstood six extra impacts of increased force before breaking on the seventh. These results demonstrated the durability of *XO Armor* standard PLA guards and indicated strong potential for their use protecting athletes. The present study aimed to expand *XO Armor's* repertoire of data-supported manufacturing options by investigating the impact strength of shoulder guards printed with methods and materials not currently utilized by *XO Armor* but available for future use.

The procedure for this study was similar to that for the previous study. The Body Opponent Bag (BOB®) shoulder scan obtained using *XO Armor's* proprietary smartphone app was used to produce seven guards: 1. Formlabs® Durable resin, solid, printed via stereolithography (SLA); 2. Formlabs® Durable resin, holed, SLA; 3. Formlabs® Tough resin, solid, SLA; 4. Formlabs® Tough resin, holed, SLA; 5. Hatchbox® PLA, solid, FDM; 6. Hatchbox® PLA, holed, FDM; 7. Raise3D® PLA, solid, FDM. The seven guards are shown in Figure 1. Each guard was positioned on the Shockshield®-draped concrete shoulder model from the previous study and impacted repeatedly with the 9 kg weighted football helmet dropped six feet from the tower. The test rig setup is shown in Figure 2A and B. It was hypothesized that for each guard, a break would occur after the first impact and on or before the tenth impact. Thus, each guard was tested no more than ten times. For each trial, a Vicon® motion capture system recorded the velocity of the helmet through impact and two AMTI® force plates recorded the impact force.

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The results of this study are summarized in Table 1. A 95th percentile male head has a mass of 5.377 kg.[1] Assuming a tackle velocity of 7.7 m/s (17.2 mph), the momentum of a head and helmet at impact is 41.4 kg m/s. As shown in the table, the guards in this study were subjected to more extreme loads with average impact momentum over 48 kg m/s. They also withstood average impact forces over 1400 lbs. Furthermore, the rigid concrete shoulder model and immovable floor create conditions more severe than a collision between two human bodies. Guards 1, 2, 3, and 5 withstood ten impacts at these conditions without breaking. Guards 4, 6, and 7 broke on the third, fifth, and second impact, respectively.

The results of this study reaffirm the strong protective potential of solid Hatchbox® PLA guards, the present *XO Armor* standard, and suggest the same for solid Formlabs® Durable resin guards, solid Formlabs® Tough resin guards, and holed Formlabs® Durable resin guards. Conversely, the early failure of the remaining guards suggests weaker protective potential.

Figure 1. Testing Guards (Top Row L-R: Formlabs® Durable resin, solid; Formlabs® Durable resin, holed; Formlabs® Tough resin, solid; Formlabs® Tough resin, holed; Bottom Row L-R: Hatchbox® PLA, solid; Hatchbox® PLA, holed; Raise3D® PLA, solid)

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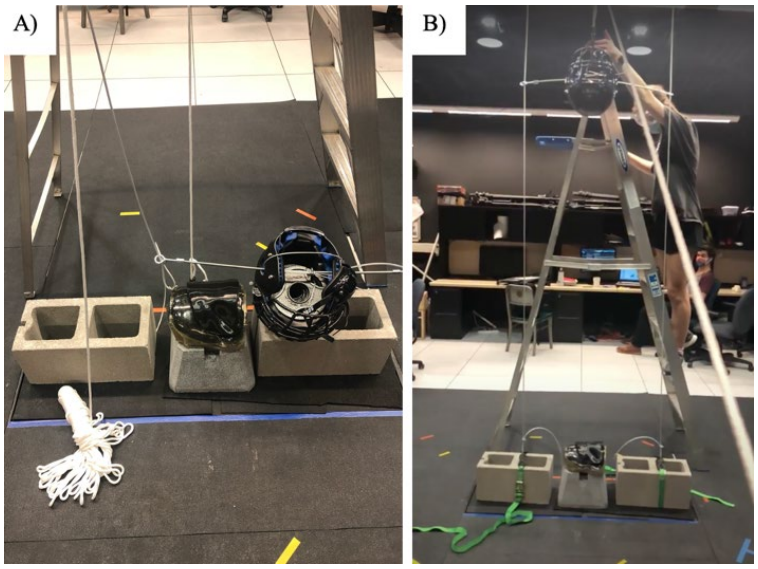

Figure 2. A) Guard On Shoulder Model and Weighted Helmet. B) Six-Foot Drop Tower Rig.

Table 1. Summary of Impact Testing Results.

Guard	Average Force (lb)	Average Velocity (mph)	Average Momentum (kg m/s)	Break Occurred
Formlabs® Durable, solid	1564.06	12.09	48.54	NO BREAK
Formlabs® Durable, holed	1609.97	12.01	48.20	NO BREAK
Formlabs® Tough, solid	1400.86	11.99	48.15	NO BREAK
Formlabs® Tough, holed	1458.51	12.09	48.53	3rd Trial
Hatchbox® PLA, solid	1512.82	12.09	48.55	NO BREAK
Hatchbox® PLA, holed	1495.34	12.08	48.51	5th Trial
Raise3D® PLA, solid	1788.80	12.12	48.65	2nd Trial

References

[1]. N. Yoganandan, F.A. Pintar, J. Zhang, J.L. Baisden. *Physical properties of the human head: mass, center of gravity and moment of inertia*. J Biomech, 42 (9) (2009), pp. 1177-1192