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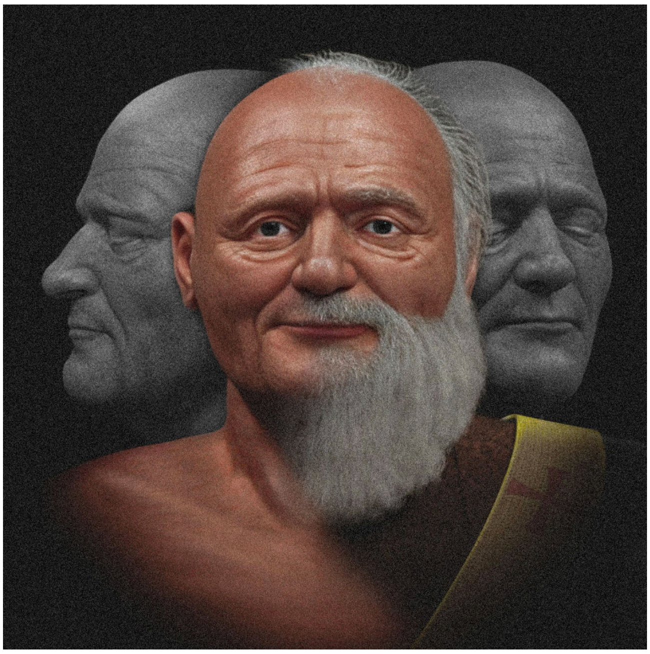
A Aproximação Facial 3D do Crânio Atribuído a São Nicolau de Mira



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Warning: O presente trabalho é independente, sem vínculo com a instituição que guarda os alegados restos mortais de São Nicolau de Mira, tampouco com as universidades e instituições que os estudaram. O elemento motivador do capítulo é a criação de material didático para o ensino da técnica de aproximação facial, ao testar a possibilidade de se reconstruir uma face utilizando dados originalmente disponíveis em matérias de jornais, mídias online, livros e *journals* acadêmicos.

Attention: Caso encontre algum erro no texto, sinta-se à vontade para informá-lo aos autores, o contato pode ser feito via redes sociais acadêmicas informadas no início do capítulo.

1.1 Introdução

1.1.1 Quem foi São Nicolau de Mira

São Nicolau de Mira ou São Nicolau de Bari, possuía ascendência grega e seria proveniente de Patara, Ásia Menor (atual Turquia), no Império Romano, onde teria nascido na segunda metade do século III (entre 250 e 270), e falecido entre os anos de 335 e 370 (6 de dezembro segundo o calendário hoje usado no Ocidente, 19 de dezembro no calendário do cristianismo oriental), em Mira, também na atual Turquia [A_Vlavianos_2011] [A_Martino_2024] . Segundo Cioffari (2024), depois da Virgem Maria, trata-se do santo que mais teve o culto difundido na Igreja Católica [A_Cioffari_2024].

Não há muitas informações históricas acerca de sua vida, exceto de que tenha sido Bispo de Mira durante o século IV. A maioria das informações biográficas estão ligadas mais a tradição do que a documentos históricos [A_Vlavianos_2011]. Segundo tal tradição ele teria sido preso durante a perseguição aos cristão perpetrada pelo imperador Diocleciano, por volta do ano 305 [A_Vlavianos_2011] [A_Petruzzello_2024]. Também é abordado que ele teria feito algumas viagens com fins religiosos, como para Alexandria, onde visitou o túmulo do evangelista São Marcos e para Jerusalém, com o objetivo de venerar lugares santos. Em 314, já retornado, é nomeado como o novo Acerbispo de Mira [A_Martino_2024].

Em 325 ele teria viajado até Bizâncio, buscando prestar homenagens à Constatino, o então emperador, e lá foi convocado para o Concílio de Nicéia, onde se discutiria a natureza de Jesus e sua relação com a figura de Deus [A_Martino_2024]. Foi naquela ocasição que teria havia um dos episódios mais populares (e contestados) acerca de São Nicolau, no qual ele teria desferido um golpe no rosto de Ário [A_Petruzzello_2024], que passava por julgamento na ocasião [A_Martino_2024], e se opunha ao conceito da eternidade de Jesus. Há no entanto algumas dúvidas sobre a participação de Nicolau no Concílio, uma vez que documentos antigos com a lista de bispos não contam com o seu nome entre os demais [A_Vlavianos_2011] [A_Kelly_2014], no entanto, parece haver casos de participapantes que lá estiveram e que não foram listados, potencialmente enfraquecendo a certezas acerca da ausência de Nicolau em tal acontecimento [A_Kelly_2014]. Após o Concílio de Nicéia, Nicolau teria viajado até Roma, para prestar homenagens ao Papa Silvestre I (270-335), que havia presidido o evento. Durante o deslocamento passou pela cidade de Bari onde teria profetizado que "Aqui meus ossos descansarão" [A_Martino_2024]. O santo teria falecido em Mira e fora sepultado em uma basílica dedicada a sua memória [A_Vlavianos_2011].

1.1.2 Os Milagres e as Relíquias

Após sua morte, já por volta do século IV a veneração a São Nicolau se popularizou na Grécia e cresceu significativamente em outros países a partir do século VI. Notabilizou-se pela caridade, se tornando o símbolo de presenteador anônimo aos que mais necessitavam [A_Vlavianos_2011]. Uma das passagens tradicionais mais populares é aquela em que um pai desesperado por não dispor de dote às filhas, se viu no limiar de forçá-las a trabalhos forçados ou mesmo a prostituição. Sabendo de tal situação, Nicolau teria jogado bolsas de ouro por três vezes na janela do pai desesperado, uma para cada filha. Quando este descobriu quem era o doador, o santo lhe pediu que mantivesse tudo em segredo [A_Vlavianos_2011] [A_Kelly_2014] [A_de_Varazze_2003].

Com o passar dos séculos a popularidade se foi incrementando, de modo que se espalhou por muitos lugares e com muita força na região da atual Itália. No final do século XI, a região de Myra estava sob domínio de turcos muçulmanos, o que causou temor por parte dos cristãos acerca da integridade dos restos mortais de Nicolau. Em face a esse potencial risco, no ano de 1087 um grupo de aproximadamente sessenta e dois marinheiros advindos de Bari, divididos em três embarcações sob o comandos do timoneiro Giannoccaro, e tendo a bordo dois padres cristãos, chegaram a Antiquoia para o transporte de grãos [A_Cioffari_2024] [A_Martino_2024]. Um grupo fortemente armado se deslocou até Mira, a três milhas, e passando-se por peregrionos, entraram na igreja onde sabidamente se encontraram os restos mortais de Nicolau e lá, rapidamente renderam os monjes guardiões, quebraram o túmulo indicado como local do sepultamento. Ao efetuarem tal ação, testemunharam a presença de uma grande quantidade de liquido, onde os ossos do santo estavam parcialmente submersos. Devido a urgência e risco, coletaram parte dos restos, deixando algumas peças para trás, não sem atestarem que o crânio estava entre a coleta [A_Martino_2024]. Os ossos foram transportados para Bari, que a partir daquele feito, se converteu em um importante centro europeu de peregrinação [A_Petruzzello_2024] e poucos anos depois, já em 1089, a Basílica de São Nicolau em Bari estava erigida e a transferência dos ossos para a capela definitiva teria a presença do então Papa, Urbano II naquele mesmo ano [A_Martino_2024].

1.1.3 De São Nicolau para Papai Noel

A Reforma Protestante, encabeçada por Martinho Lutero (1483-1546) foi um movimento que colaborou com o desaparecimento da devoção a São Nicolau, nos países que abraçaram essa vertente religiosa. Uma exceção notável foi na Holanda, onde a lenda de Sinterklaas (supressão linguística do nome do santo) seguiu forte, inclusive influenciando as colônias daquela nação. Uma destas colônias era a cidade de Nova Amsterdã, hoje Nova Iorque, onde a lenda se anglicizou no nome Santa Claus, descrita como um velho senhor que punia crianças descomportadas e premiava as que apresentavam bom comportamento, com presentes [A_Petruzzello_2024].

A imagem que hoje se conhece do Papai Noel foi baseada na ilustração de Thomas Nast (1840-1902), para a revista Harper's Weekly no começo de 1863 (Fig.1.1), que por sua vez foi inspirado na descrição do poema "A Visit from St. Nicholas" (https://poets.org/poem/visit-st-nicholas), atribuído a Clement Clarke Moore ou Henry Livingston, publicado anonimamente em 1823 e que já apresentava muitas das características atribuídas ao "bom velhinho", como a aparência "gordinha e rechonchuda", as bochechas rosadas, um comportamento simpático, o trenó voador puxado por renas, o acesso pela chaminé e um saco de brinquedo nas costas. Após quase sete décadas depois da publicação de Nast, a partir de 1931, a Coca-Cola Company lançava uma campanha com ilustrações de Haddon Sundblom (1899-1976) que apresentava a figura que hoje é amplamente divulgada como a do Papai Noel, ou seja, um senhor de idade avançada, de aparência rechonchuda, com roupa vermelha, cinto preto, decoração em pelos brancos, botas pretas e um gorro vermelho [A_Petruzzello_2024b].

Apesar da complexidade e do caldeirão de cul-

Figure1.1: Desenho de Santa Claus efetuado por Thomas Nast em 1863i. Wikimedia Commons - imagem sob domínio público (https://upload.wikimedia.org/wikipedia/commons/d/d5/Nast_Santa_cropped%2C_1881.png)

turas que envolvem a evolução dos símbolos natalinos, é bastante evidente a ligação entre São Nicolau de Mira e o Papai Noel [A_de_Ceglia] [A_Kelly_2014] [A_Martino_2024] [A_Vlavianos_2011] [A_Petruzzello_2024] [A_Petruzzello_2024b].

1.1.4 Os Exames Anatômicos de 1953 e 1957

No início dos anos 1950 foram identificadas algumas infiltrações subterrâneas que poderiam comprometer a estrutura da Basílica de São Nicolau em Bari (https://www.basilicasannicola.it/). Por conta das obras de reparo, a cripta contendo os restos de São Nicolau precisaria ser esvaziada rapidamente. O trabalho de retirada dos restos foi organizado por uma comissão especial, sob as ordens do Papa Pio XII [A_Martino_2024]. Na ocasião, a análise dos ossos ficou a cargo do Dr. Luigi Martino (1908 - 2001), professor da Universidade de Bari na Faculdade de Medicina, Farmácia, Ciências Naturais, de Anatomia Humana Normal, Histologia e Embriologia.

Na passagem do dia 5 para 6 de maio de 1953, o Dr. Martino, juntamente com outros especialistas removeram as pesadas lajes que cobriam o túmulo de Nicolau de Mira. Segundo o especialista, ao acessarem o nicho monolítico atestaram que o mesmo, a exemplo do que se passou em 1087, também continha água envolvendo os ossos; o líquido cristalino receberia o nome de maná, cujos relatos foram colhidos ao longo dos séculos [A_de_Ceglia]. O Dr. Martino efetuou uma detalhada catalgação dos restos mortais, que se configuraram em um esqueleto incompleto e enviou os resultados dos levantamentos para o Vaticano [A_Martino_2024].

As obras se estenderam por quatro anos, até 1957, e durante esse período os ossos foram colocados em uma caixa de madeira com uma pequena janela, de modo que os fiéis pudessem visualizar as relíquias. Antes da realocação dos restos à cripta, o Dr. Martido e equipe efetuaram mais um detalhadado estudo anatômico. A análise apresentou uma série de dados métricos como a altura estimada de 1.67 m, entre e outras medidas. Tais dados permitiram a elaboração de uma trivisão coordenada, um conjunto de três planos bidimensionais com informações ortográficas do crânio, que por sua vez permitiram ao especialista traçar um identikit, grosso modo, a representação gráfica de como seria o rosto do santo em vida, que apresentou uma característica marcante: a assimetria nasal [A_Martino_2024].

1.1.5 As Relíquia do Lido de Veneza

No ano de 1992 o Dr. Martino foi convidado a analisar uma pilha de fragmentos ósseos atribuídos a São Nicolau de Mira, sob os cuidados da Igreja de San Nicolò no Lido de Veneza. Tais relíquias teriam sido capturadasem Mira, no ano de 1100 e transportadas para Lido, em uma situação semelhante aquela efetuada pelos marinheiros de Bari alguns anos antes [VisitLido] [A_Martino_2024]. Uma série de seis trabalhos de reconhecimento das relíquias haviam sido efetuados anteriormente, inclusive com a identifcação de um recipiente com maná condensado, mas todos estavam mais ligados à questão religiosa e cerimoniais, sendo assim as autoridades eclesiásticas de Veneza buscaram o contato do Dr. Martino, um acadêmico que havia estudado as relíquias de Bari, buscando uma confirmação mais robusta acerca dos restos mortais. O especialista analisou os ossos, organizou-os e através de um esquema gráfico, ilustrou que havia uma compatibilidade entre os ossos faltantes de Bari e os disponíveis em Lido, o que denotaria o pertencimento a um único esqueleto.

1.1.6 As Reconstruções Faciais

A primeira tentativa de aproximação facial foi o supracitado identikit do Dr. Martino nos anos 1950 [A_Martino_2024].

Na primeira metade dos anos 2000, o Dr. Francesco Introna, especialista em Medicina Legal pela Universidade de Bari encabeçou um projeto que daria uma face 3D a São Nicolau. Utilizando os dados coletados pelo Dr. Martino em 1953-57 (fotografias e radiografias), a especialista reconstrução facial forense Dr. Caroline Wilkinson efetuou uma representação de como poderia ser o rosto de São Nicolau de Mira, em um tom de pele pardo [A_Mahoney_and_Wilkinson_2012]. O trabalho foi apresentado no documentário da Atlantic Productions intitulado “The Real Face of Santa” (https://www.imdb.com/title/tt2032556/).

Dez anos depois, em 2014 uma nova versão, com um tom de pele mais claro foi apresentado, também pela Dra. Caroline Wilkinson em parceria com a Universidade Liverpool John Moores [A_BBC_2014].

1.1.7 A Aproximação Facial de 2024

O presente trabalho nasceu de uma ampla tradição, por parte dos autores, de aproximações faciais envolvendo figuras religiosas da Igreja Católica, algumas com participação direta dos responsáveis pelos restos mortais, como os casos de Santo Antônio de Pádua em 2014 e 2023 [A_Moraes_et_al_2023], Santa Ludmila da Boemia [A_Moraes_et_al_2023b], São Adalberto de Praga [A_Erpen_2024], Santa Catarina de Gênova [A_Erpen_2019] e outras, totalizando mais de 20 santos e beatos (https://www.ciceromoraes.com.br/doc/pt_br/Moraes/RFF_Religiosas.html). Em sua grande maioria, a exemplo deste material, as images resultantes dos processos estão disponíveis sob licença livre Creative Commons.

1.2 Materiais e Métodos

A reconstrução facial forense (RFF) ou aproximação facial forense (AFF) [A_Stephan_2015], é uma técnica auxiliar de reconhecimento que reconstrói/aproxima a face de uma pessoa a partir do seu crânio e é utilizada quando há escassa informação para a identificação de um indivíduo [A_Pereira_et_al_2017]. Nota-se que a técnica não se trata de identificação, como aquelas oferecidas por DNA ou análise comparativa de arcos dentários, mas sim de reconhecimento que pode levar à posterior identificação [A_Baldasso_et_al_2020].

Todo o trabalho disponível neste capítulo foi efetuado utilizando software livre e gratuito, majoritamente no ambiente do Blender 3D, através do addon OrtogOnBlender [A_Moraes_et_al_2020], que por sua vez conta com um submódulo específico para AFF, intitulado ForensicOnBlender.

Attention: Além da AFF o OrtogOnBlender é utilizado para o planejamento de cirurgia ortognática [A_Cunha_et_al_2020] [A_Lobo_et_al_2022], rinoplastia [A_Sobral_et_al_2021], fraturas mandibulares [A_Facanha_et_al_2021], expansores mandibulares de bebês [A_Duarte_et_al_2023], documentação urológica [A_Nascimento_et_al_2023], próteses veterinárias [A_Taub_2024], próteses faciais [A_Salazar_et_al_2022] e outros, por usuários de 30 países, contemplando 4 continentes.

Inicialmente buscou-se reconstruir o crânio em 3D, tal processo foi efetuado utilizando os dados estruturais presentes no livro “Le Reliquie di S. Nicola” [A_Martino_1987], de autoria do Dr. Muigi Martino e cuja autorização um dos autores (C.M) solicitou via e-mail ao Pe. Gaetano Gerardo Cioffari, do Centro Studi Nicolaiani (http://www.centrostudinicolaiani.it/), que gentilmente o permitiu.

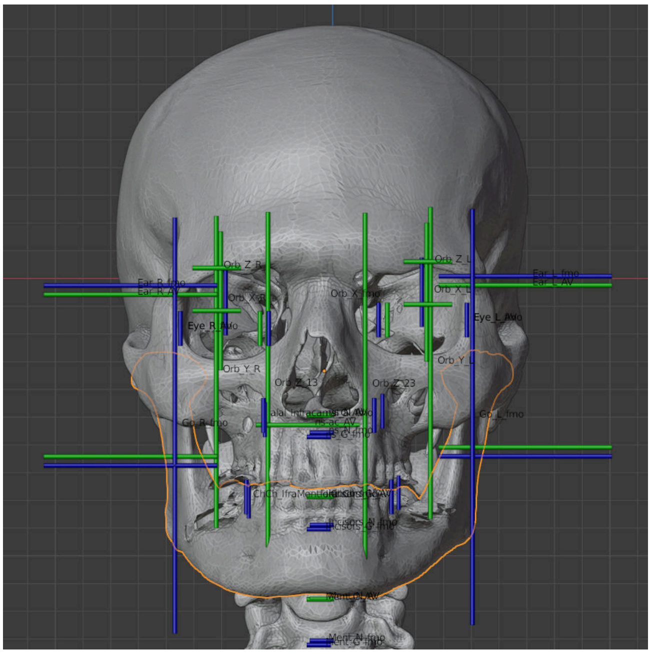

Figure1.2: Crânio reconstruído.

O crânio resultante foi alinhado ao plano de Frankfurt e passou pela projeção das estruturas do osso e tecido mole fornecidas pela ferramenta do OrtogOnBlender que utiliza os dados de uma série de medições efetuadas em tomografias de indivíduos vivos [A_Moraes_and_Suharschi_2022]. Como se trata de um trabalho de reconstrução indireta, não foi possível aferir com total clareza a estrutura craniana, mas a mesma parecia contar com alguns alvéolos o que denotaria a presença dos dentes no momento da morte. O modelo utilizado indicou que a posição da mandíbula poderia ser corrigida, sendo levemente mais aborta, para se adequar a projeção estatística, então essa correção foi efetuada para aumentar a coerência anatômica baseada em tal modelo (Fig.1.2). Para uma compreensão prática do funcionamento da solução, duas videoaulas sobre projeções estruturais estão disponíveis de modo online em: aula 1[5], aula 2[6].

O passo seguinte consistiu na distribuição de marcadores de tecido mole, referente a um grupo de indivíduos do sexo masculino de 60 a 69 anos [A_De_Greef_2006]. Para a projeção nasal foi utilizada a abordagem complementar proposta por [A_Moraes_2021]. Uma video aula[7] sobre a técnica de projeção nasal pode ser acessada de modo online.

O crânio apresentou uma estrutura significativamente mais estendida no eixo X (horizontal) do que o esper-

[5] https://youtu.be/U6oYkEmfyWo
[6] https://youtu.be/Vcz2e5uSFX8
[7] https://youtu.be/F205kLQ--Oo

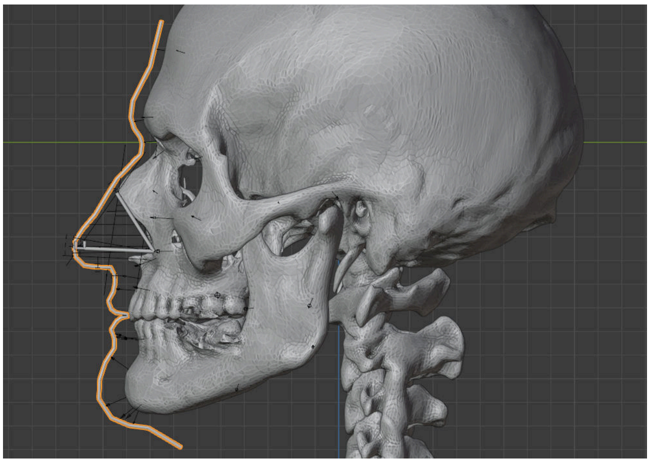

Figure1.3: Marcadores de espessura de tecido mole, projeção nasal e do perfil do rosto.

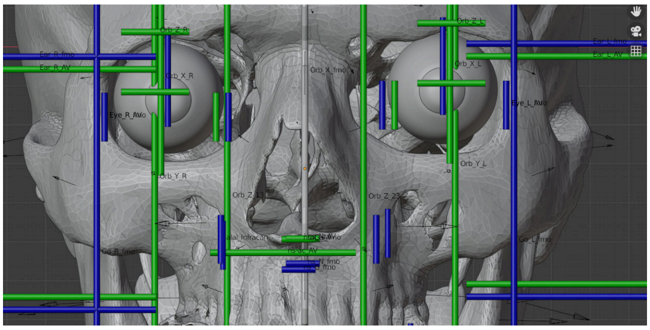

Figure1.4: Posicionamento dos globos oculares.

ado, em face desta carasterística o posicionamento dos globos oculares respeitou a mais a proporção (linhas em azul) do que a média (linhas em verde) (Fig.1.4).

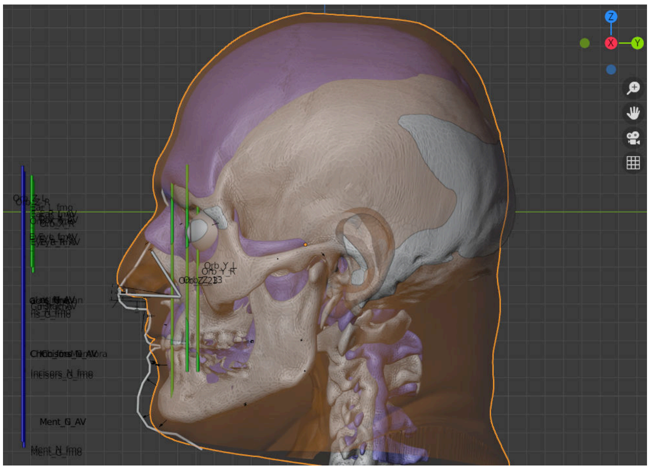

Figure1.5: Importação do doado virtual.

Para complementar os dados das projeções anteriores, a malha de um doador virtual, composta pela crânio e tecido mole foi importada e alinhada na cena (Fig.1.5). Tal malha é a base para o processo de deformação anatômica, que consiste em ajustar a estrutura até que o crânio do doador se compatibilize ao crânio cuja face será aproximada [A_Quatrehomme_et_al_1997].

Como a modificação é feita em vários pontos da cabeça, com uma esfera de influência decrescente, ao se ajustar a malha total focando no crânio, espera-se que, como aconteceu neste caso, o rosto ajustado se compatibilize com o perfil traçado a partir das projeções (Fig.1.6). Uma videoaula abordando a deformação anatômica pode ser acessada de modo online[8].

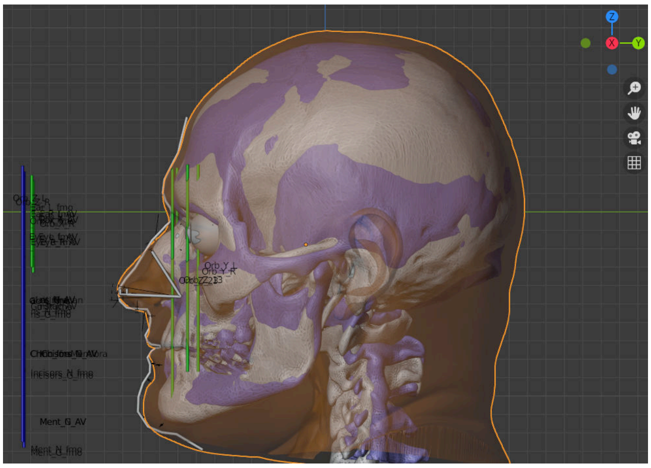

Figure1.6: Ajuste do doado virtual.

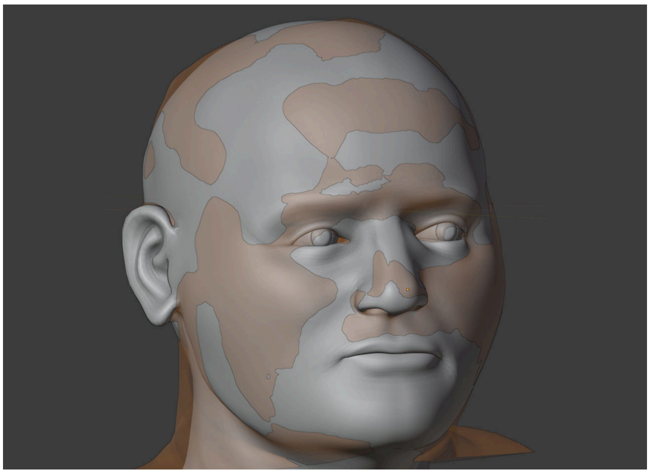

Figure1.7: Busto básico.

Um busto básico é gerado da interpolação dos dados das projeções e da deformação anatômica, resultando em uma estrutura significativamente robusta (Fig.1.6).

Os dados relacionados a projeção nasal respeitam uma média de idade populacional, que se encontra abaixo da faixa etária do crânio atribuído a São Nicolau, sendo assim, a rotação da ponta do nariz é ajustada para refletir as mudanças que podem ocorrer com o passar dos anos, extrapolando os dados de [A_Shastri_et_al_2021].

A etapa seguinte envolve os detalhes mais finos de escultura digital para a criação das linhas de expressão, a configuração dos pelos e cabelos e ajuste da indumentária (Fig.1.9).

A etapa final consistiu na pigmentação da pele e dos cabelos, cruzando dados da iconografia e trabalhos anteriores de aproximação facial. Após a ger-

[8] https://youtu.be/xig5_EcIFWA

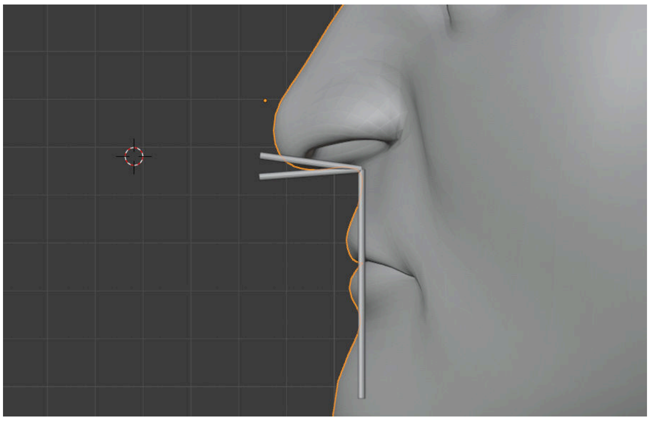

Figure1.8: Ajuste do ângulo nasal pela idade.

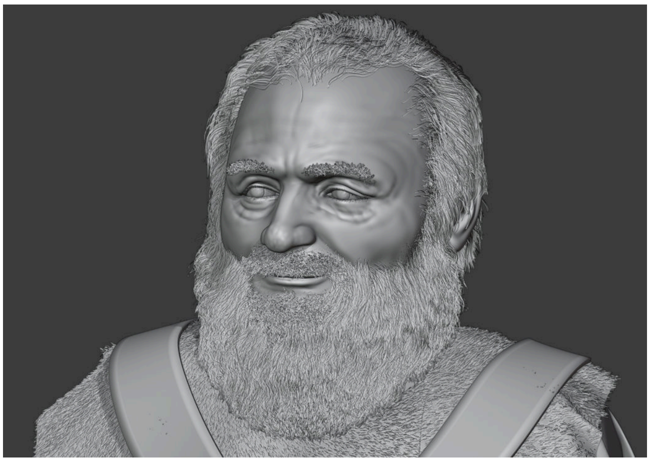

Figure1.9: Detalhamento das expressões, pelos, cabelos e indumentária.

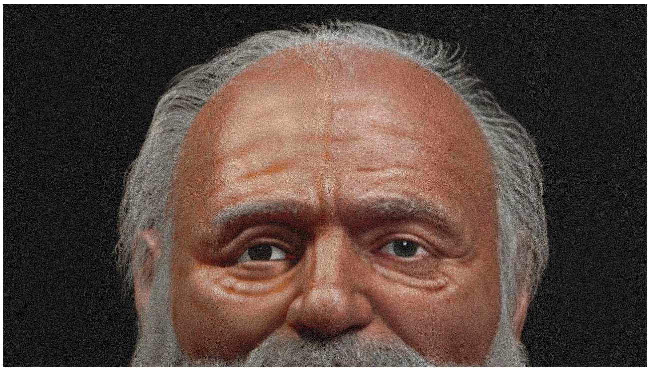

Figure1.10: Renderização original à esquerda e correções por IA à direita.

ação da imagem, os detalhes faciais foram incrementados pelo uso de IA, através da solução CodeFormer [A_Zhou_et_al_2022], tomando-se o devido cuidado para tal processo manter a estrutura original da face, sem desconfigurá-la (Fig.1.10). Ainda que a ferramenta de melhoramento apresentasse um resultado globalmente bom, foram necessárias algumas correções manuais na edição de imagem via The Gimp (www.gimp.org).

1.3 Resultados e Discussão

Foram geradas 6 imagens no processo de renderização: 1) Três com os elementos mais objetivos face, sem pelos e cabelos, em escala de cinza e com os olhos fechados, desta forma evita-se apresentar detalhes dos quais não há maior certeza (Fig.1.11, Fig.1.12, Fig.1.13). 2) Três com elementos mais artísticos e especulativos, como a coloração da pele, pelos e cabelos, coloração e forma dos olhos e indumentária (Fig.1.14, Fig.1.15, Fig.1.16).

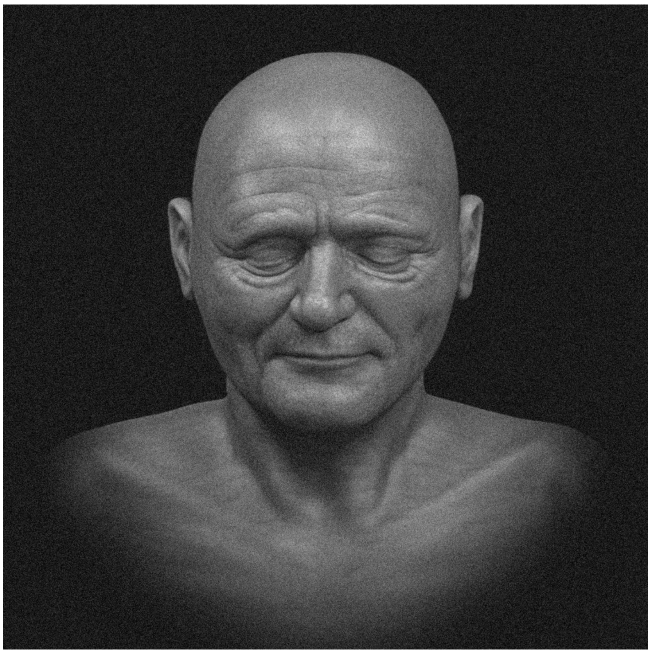

Figure1.11: Face objetiva com vista frontal levemente superior, evidenciando a assimetria nasal.

O resultado das renderizações evidenciam que um nariz assimétrico, como é o caso do crânio aproximado, pode gerar estruturas faciais ligeiramente diferentes, dependendo do ponto de vista. Os elementos artísticos e mais subjetivos como a barba ocultam significativamente a face, podendo desconfigurar o indivíduo, dando a impressão de que se trata de outra pessoa. No entanto, o presente caso curiosamente gerou uma imagem compatível com a primeira gravura do Papai Noel, aquela de 1863 que fora por sua vez baseada em um pema que descrevia um rosto largo ou amplo (broad face). Um estuto efetuado em 2019 que comparou um osso pertencente ao esqueleto atribuído a São Nicolau, com um indivíduo moderno, de idade semelhante (aproximada-

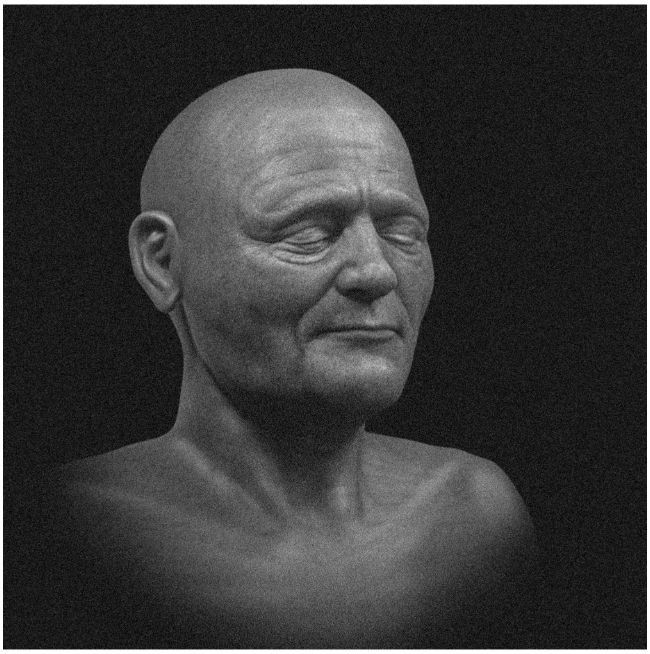

Figure1.12: Face objetiva com lateral direita.

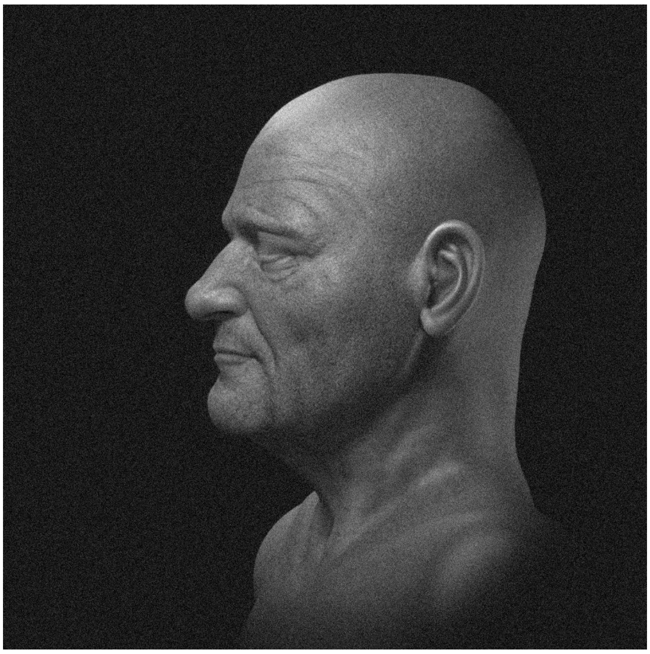

Figure1.13: Face objetiva com visão de perfil, a assimetria causa a impressão de uma face levemente diferente da vista leteral direita.

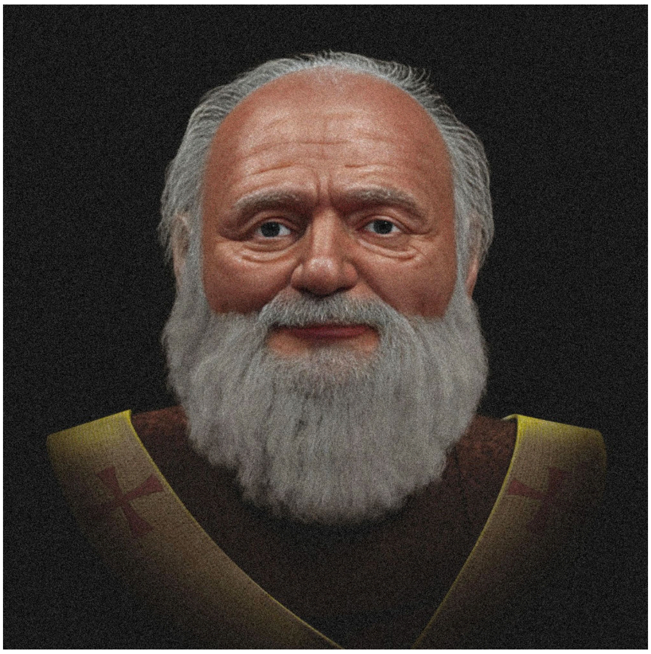

Figure1.14: Face artística frontal.

Figure1.15: Face artística com visão lateral esqeurda levemente superior.

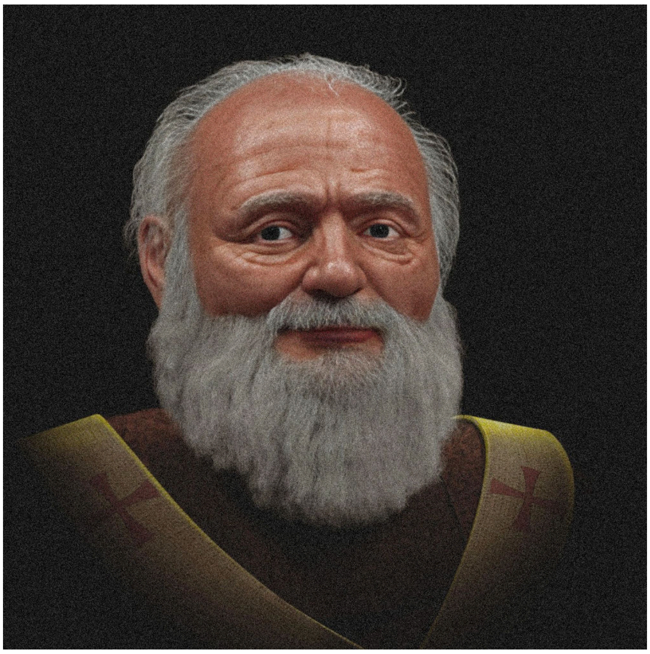

Figure1.16: Face artística com visão lateral fireita.

mente 70 anos) e saudável, indicou que a relíquia apresenta uma densidade 168% maior do que o segundo [A_Rubuni_et_al_2019]. Junte-se tal informação a estrutura claramente robusta do crânio e pode-se inferir que, há a possibilidade de se tratar de um indivíduo com forte compleição física. Pertencendo o crânio a São Nicolau ou não, o fato é que a complexidade do desenvolvimento histórico e cultura ao longo destes séculos, pode permitir que, eventualmente, algumas coincidências sejam produzidas.

1.4 Conclusão

O presente capítulo objetivou apresentar uma aproximação facial forense a partir de dados disponíveis digitalmente. Aplicando uma metodologia estabelecida anteriormente, foi possível apresentar novas imagens em um trabalho com licença aberta e que pode motivar estudos e debates, além de evidenciar um pouco da história de São Nicolau de Mira e dos supostos restos mortais do santo.

1.5 Agradecimentos

Ao Dr. Richard Gravalos, por ceder a tomografia computadorizada utilizada neste estudo. Ao Pe. Gaetano Gerardo Cioffari que gentilmente autorizou o uso dos dados presentes na obra do Dr. Luigi Martino. Ao Sr. Antonio Rana, auxiliou-nos na busca de informações presenciais em Bari, Itália.

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Chapter 2

Sistema Unificado para a Criação de um Crânio Composto no OrtogOnBlender XP

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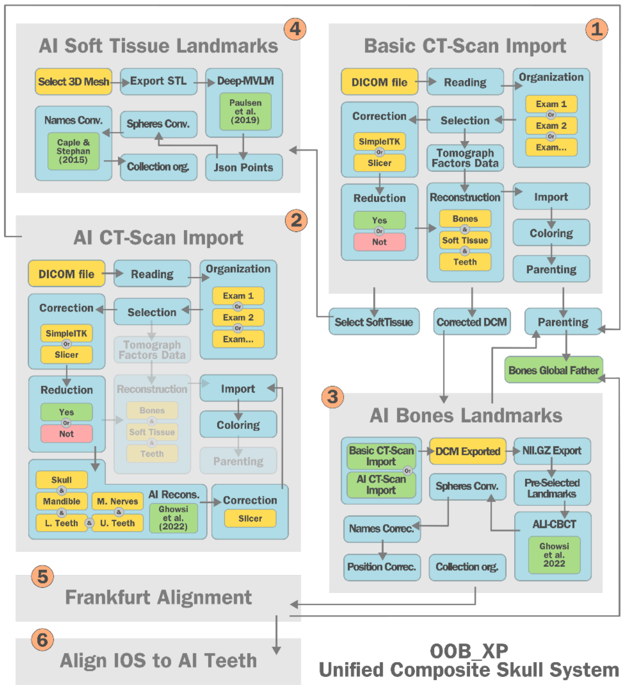


2.1 Introdução

O presente capítulo apresenta a ferramenta unificada de reconstrução de tomografia computadorizada e criação de crânio composto, que está sendo desenvolvida para o OrtogOnBlender XP (OOB_XP), uma versão baseada no Blender 4.2 LTS, inicialmente para o Linux Ubuntu 24.04 LTS e o Windows, com planejamento de expansão para o MacOS.

2.2 Como Funciona

O funcionamento da ferramenta é basicamente o mesmo daquele explanado em [B_Moraes_et_al_2024], onde o usuário inicialmente informa o local onde se encontram os arquivos DICOM e posteriormente indica qual exame pretende que seja reconstruído em 3D (Fig.2.1).

A diferença fundamental para ativar o sistema unificado é clicar no check button "REC-SEG-PTS-FRANKFURT". Assim que a ação é efetuada, a interface se expande, apresentando dois campos de seleção dos arquivos STL das arcadas superior (Up. IOS) e inferior (Lo. IOS) (Fig.2.2). A seleção é opcional, o sistema pode rodar sem que tais arquivos sejam setados, no entanto, é praxe que em um planejamento os escaneamentos intraorais (IOS) estejam presentes. Uma vez

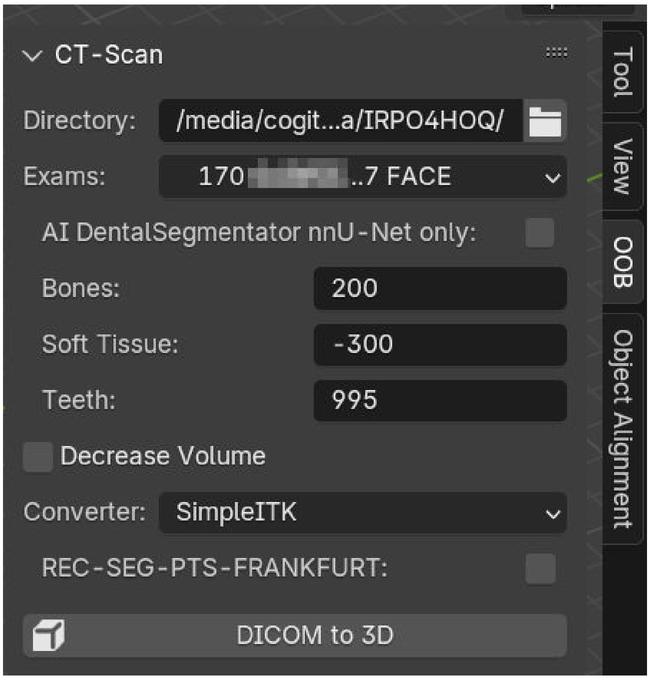


Figure2.1: Etapa inicial da configuração.

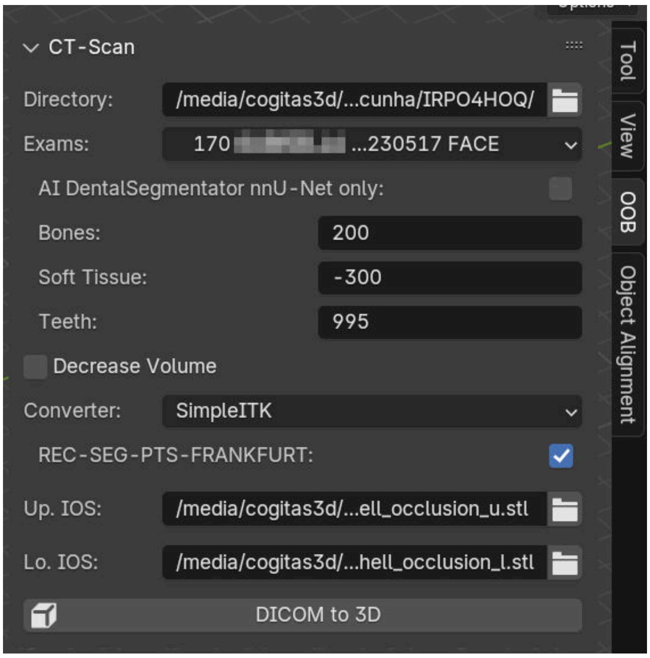


Figure2.2: Dados prontos para a reconstrução.

configurado, o botão "DICOM to 3D", logo abaixo, pode ser pressionado, dando início ao processo.

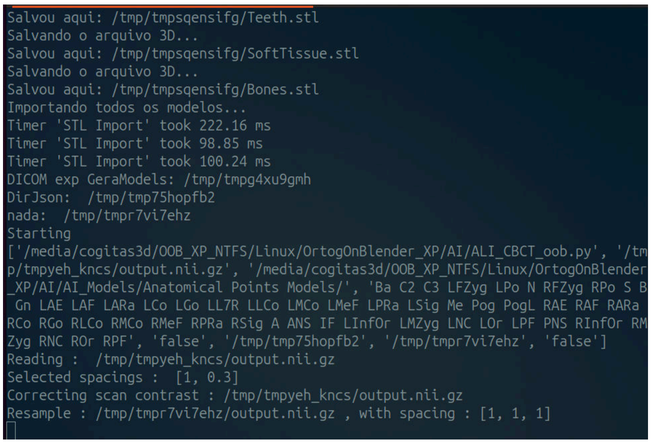


Figure2.3: Processo unificado rodando em background.

As etapas de trabalho passarão a rodar em background e podem ser companhadas pelo terminal (Fig.2.3).

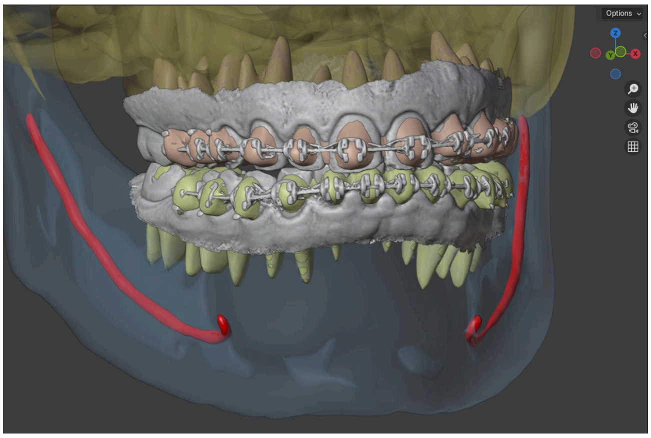


Figure2.4: Finalização bem-sucedida de todas as etapas do método unificado.

Após alguns minutos a interface é atualizada com o resultado do processo, resultando no caso do exemplo, na reconstrução de todos os tecidos (mole e ósseo), além da segmentação de regiões de interesse, bem como no alinhamento dos modelos dos dentes às segmentações das arcadas (Fig.2.4). É importante deixar claro que a etapa final, ou seja, o alinhamento dos dentes nem sempre é bem sucedido como no exemplo desde material, sendo necessária uma etapa complementar de alinhamento, mas mesmo assim, a evolução em relação à versão anterior é significaticamente grande.

Caso os modelos não estejam satisfatóriamente alinhados às arcadas, uma etapa complementar de ajuste pode ser feita através do botão "Fix IOS to CT" (Fig.2.5). Como as estruturas estão nomeadas, o sistema se encarrega de proceder com os comandos, sem a necessidade do usuários selecionar nenhuma das malhas, bastando apenas ajustar uma melhor posição dos modelos para ajudar o algoritmo de alinhamento. Caso o alinhamento se estabeleça de modo satisfatório, o usuário

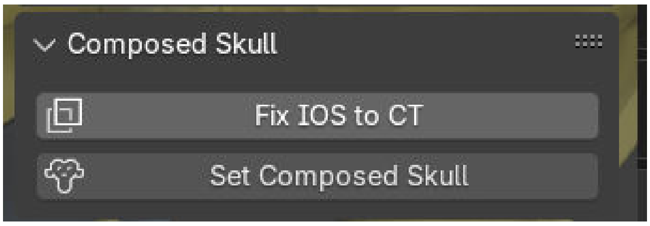


Figure2.5: Ajuste no alinhamento das arcadas.

poderá clicar em “Set Composed Skull”, para criar o crânio composto.

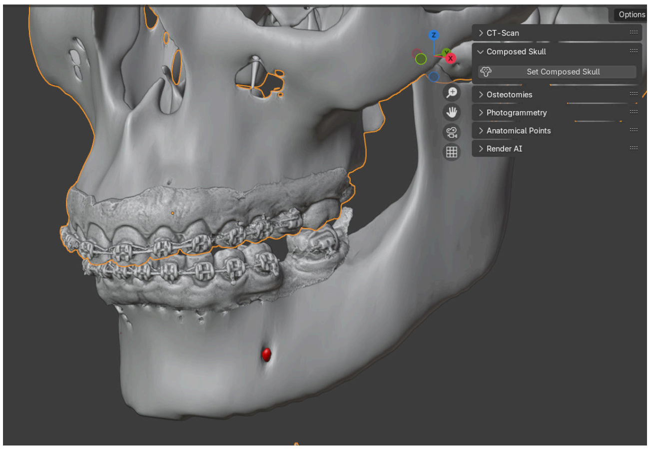


Figure2.6: Criação do crânio composto.

O sistema se encarregará de fundir os modelos com o crâno e a mandíbula, gerando o crânio composto em duas peças separadas, a “Composed_Skull” e a “Composed_Mandible” (Fig.2.6).

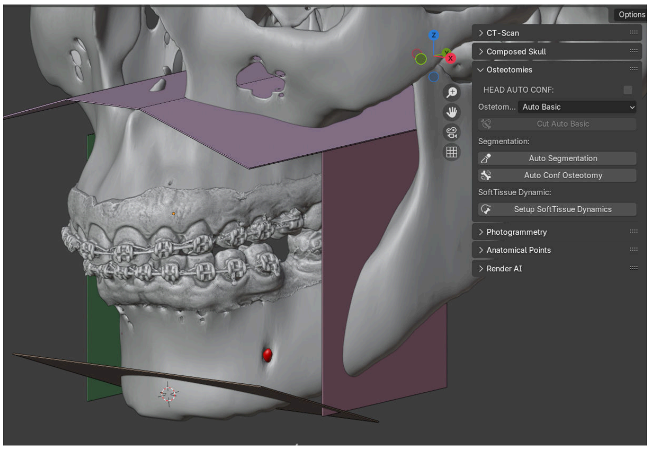


Figure2.7: Planos de corte criados.

Uma vez que o crânio composto esteja finalizado, é possível inserir os planos de corte na cena. Para isso é preciso expandir a seção “Osteotomies” e clicar em “Cut Auto Basic”, assim o sistema utilizará como referência os pontos anatômicos automaticamente posicionados nos ossos para distribuir os planos de corte (Fig.2.7). Na imagem de exemplo o botão está desabilitado, pois acabou de ser usado, tornando desnecessário o comando, no entanto, há a possibilidade do usuário posicionar manualmente um por um dos planos de corte, bastando para isso trocar a opção de “Auto Basic” no menu logo acima, para “Manual Basic”.

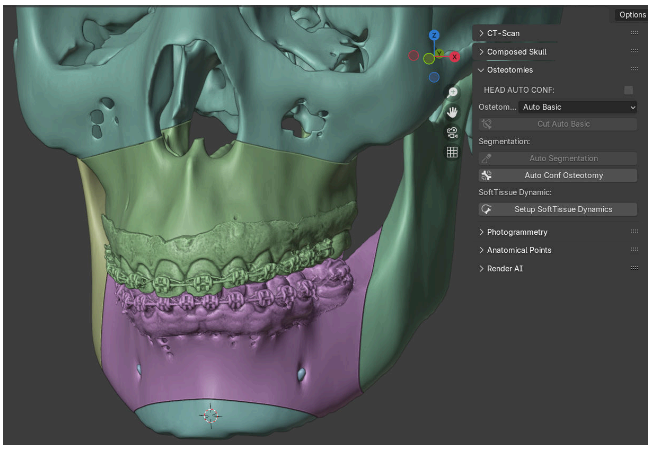


Figure2.8: Auto segmentação.

Apesar do sistema distribuir os planos de corte em locais coerentes com os objetivos da cirurgia ortognática, é imprescindível que o especialista ajuste as estruturas conforme as necessidades avaliadas por ele. Em seguida, basta clicar em “Auto Segmentation” para que as segmentações (osteotomias) se efetivem. O OOB_XP automaticamente troca o tipo de visualização de cores para random, de modo que o usuário avalie se o processo de corte foi bem sucedido (Fig.2.8). Novamente, não é necesserário fazer nenhum tipo de seleção, pois o sistema o faz de modo autônomo. Apesar do OOB_XP fazer um a limpeza automática em malhas que não satisfaçam as estruturas esperadas para uma osteotomia, o usuário precisará checar se o número de ossos está correto e se tem algum resíduo indesejado. Sabendo-se que as osteotomias estão corretas, o usuário pode prosseguir com o próximo comando, que implica em clicar no botão “Auto Conf Osteotomy”.

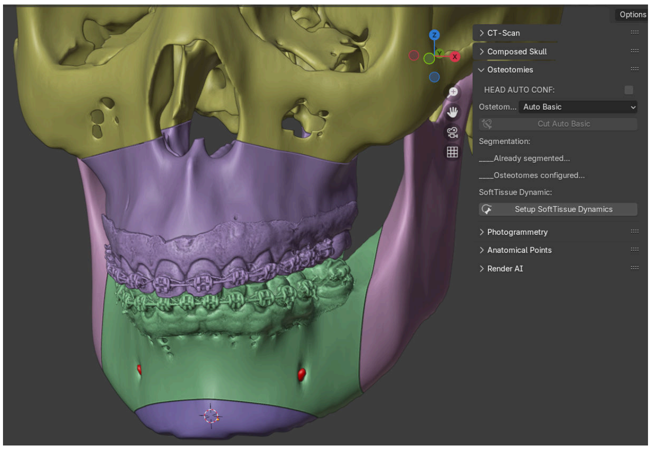


Figure2.9: Configuração das osteotomias.

O sistema se encarrega de fazer a configuração dos ossos, nomeando-os e criando a estrutura que será utilizada para a deformação do tecido mole (Fig.2.9). Conforme os botões vão sendo utilizados e as condições satisfeitas, alguns deles são desabilitados ou sofrem uma alterçação de estrutura, não sendo possível clicar novamente nos mesmos (a menos que se apaguem algumas estruturas ou se use o comando de voltar). Estando tudo ajustado, o usuário pode clicar em "Setup SoftTissue Dynamics" para configurar a deformação do tecido mole.

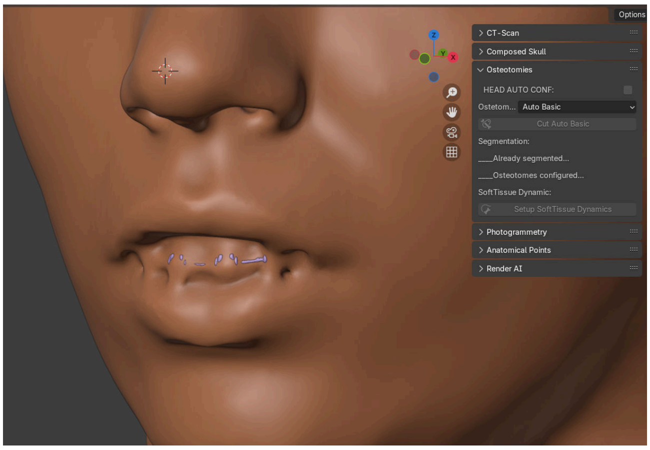


Figure2.10: SoftTissue dynamic efetuado.

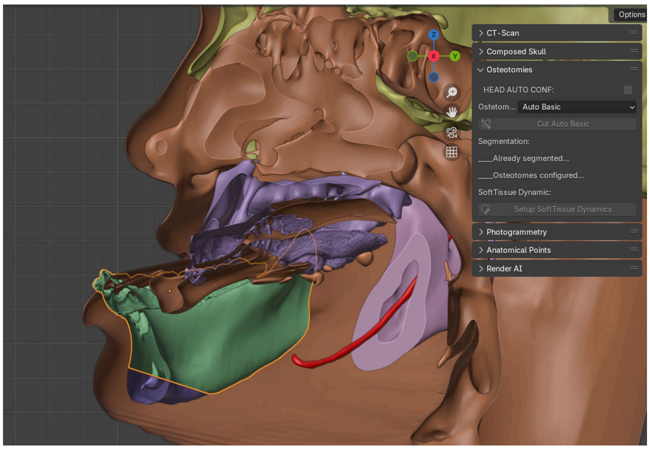


Figure2.11: Teste de deformação.

Novamente não é necessário fazer nenhum tipo de seleção, pois o OOB_XP se encarrega de projetar as áreas de deformação conforme as osteotomias (Fig.2.10), além de fazer correções nos limites dos lábios, o que não estava disponível na versão anterior do add-on. Não é necessário o usuário selecionar a malha do tecido mole, tampouco torná-la visível, pois o add-on faz isso automaticamente (Fig.2.11).

2.3 Detalhes Técnicos e Testes

2.3.1 Estrutura dos Comandos

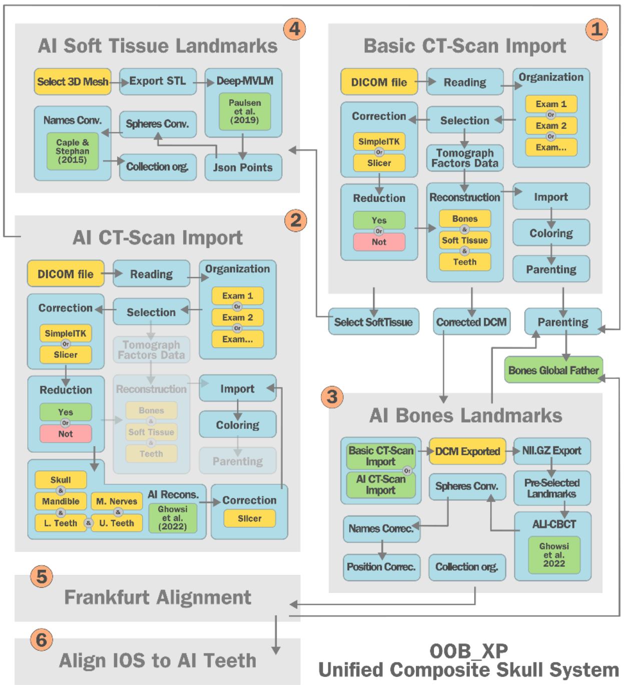


Figure2.12: Esquema do sistema unificado para a criação do crânio composto.

O sistema unificado para a criação do crânio composto é uma evolução de abordagens que vêm sendo testadas e utilizadas no OrtogOnBlender ao longo dos anos, com a incrementação de novas ferramentas baseadas em inteligência artificial. O esquema simplificado (Fig.2.12) ilustra como a estrutura funciona:

1) **Basic CT-Scan Import**: Depois do usuário selecionar o exame que se pretende trabalhar, a reconstrução básica dos ossos, tecido mole e dentes é efetuada. Tal passo é necessários, pois é dali que sairá a malha do tecido mole (SoftTissue) usada na deformação cirúrgica, o crânio (Bones) que será o pai de todas as outras malhas e os dentes (Teeth) que fornecerão dados complementares da estrutura dos dentes e eventualmente de algum artefato de metal presente na cabeça. Essa etapa foi descrita em [B_Moraes_et_al_2024].

2) **AI CT-Scan Import**: Em seguida há uma etapa de segmentação do crânio, da mandíbula, da arcada superior, arcada inferior e dos nervos mentuais. Essa fase simplifica muito o trabalho, pois ao usuário será poupada a etapa, muitas vezes enfadonha, de segmentação manual. As malhas resultantes são parenteadas como filhas do crânio principal (Bones). Essa ferramenta foi descrita em [B_Moraes_et_al_2024b]. *Leitura complementar* [B_Dot_et_al_2024] [B_Isensee_et_al_2020].

3) **AI Bones Landmarks**: Com as estruturas reconstruídas, outra ferramenta baseada em inteligência artificial foi utilizada para econtrar uma série de pontos anatômicos no tecido ósseo. Tal ferramenta já havia sido estudada anteriormente e está descrita em [B_Moraes_et_al_2024c]. *Leitura complementar:* [B_Gillot_et_al_2023].

4) **AI Soft Tissue Landmarks**: Um importante passo foi adicionado no processo, este utiliza a inteligência artificial para distribuir uma série de pontos ao longo da malha da face. A ferramenta está descrita em [B_Paulsen_et_al_2019] e passou por algumas adaptações para se adequar à interface gráfica do OOB_XP, como a conversão dos números dos pontos em nomes das regiões anatômicas, tomando como referência o trabalho de [B_Caple_and_Stephan_2015].

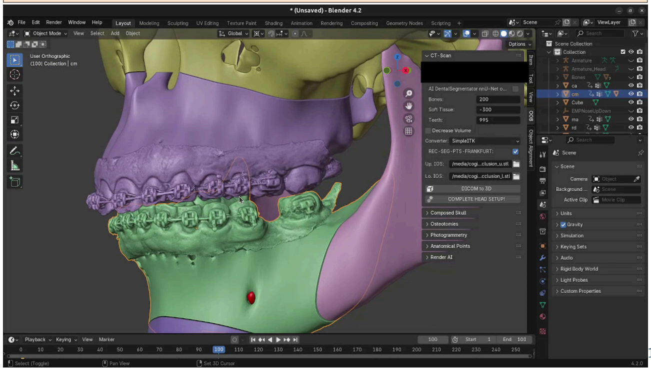
5) **Frankfurt Alignment**: Utilizando os dados dos pontos anatômicos, além de alguns parâmetros para fortalecer a coerência estrutural, o crânio principal é alinhado ao plano horizontal de Frankfurt e uma vez que os demais elementos da cena estão parenteados a ele, todos seguem a rotação.

6) **Align IOS to AI Teeth**: Uma série de comandos implementados pelos autores posiciona os modelos dos dentes (IOS) próximos aos dentes extraídos pelas ferramentas de AI e refinam o alinhamento com ICP, a partir do trabalho de Moore et al. (https://github.com/patmo141/object_alignment).

Todas as ferramentas receberam camadas adicionais de ajustes para que o resultado fosse unificado em apenas um espaço e interface gráfica. O OOB_XP complementou as etapas com mecanismos anti-erro, de modo que o usuário tenha o mínimo de interação e o máximo de acerto ao utilizar a solução.

Posteriormente foram portadas outras ferramentas à interface do OOB_XP, como o posicionamento automático de planos de cortes (osteotomias), o próprio corte digital (boolean), a configuração automática das osteotomias e finalmente a configuração da deformação do tecido mole. Tais ferramentas já faziam parte das versões anteriores do OOB, bem como já haviam passado por comparações do estilo *planejamento digital vs. pós cirúrgico real* [B_Cunha_et_al_2020] [B_Lobo_et_al_2022], resultando em significativa compatibilidade. Tais ferramentas passaram por um processo de melhoramento funcional, graças à experiência e feedback dos usuários, bem como com o incremento da AI no código.

Attention: Durante o desenvolvimento da ferramenta, foi criado um botão com uma cadeia de comandos, envolvendo todos os processos descritos acima, bastando ao usuário indicar o local dos arquivos DICOM, qual exame seria utilizado e a informação dos IOS superior e inferior. Com essas informações o OOB_XP foi capaz de, sem a intervenção do usuário, proceder autonomamente desde a reconstrução da tomografia, segmentação, alinhamento em Frankfurt, passando pelo alinhamento dos IOS às segmentações dos arcos, fundindo as estruturas para a criação do crânio composto, posicionando os planos de corte, efetuado as osteotomias, configurando as osteotomias e a deformação do tecido mole. Um vídeo timelapse foi gravado, ilustrando todo o processo: https://youtu.be/RRLIiqwSMKk.


[13]

Para assistir o vídeo clique sobre o thumbnail acima ou no link da caixa informativa.

Warning: Embora seja possível proceder de modo automático com todos os comandos descritos acima, os desenvolvedores não recomendam que isso seja efetuado durante o processo de planejamento cirúrgico, uma vez que a participação do cirúrgião nas decisões é essencial para uma simulação bem sucedida, reforçando a segurança do processo.

2.3.2 Testes

Seguindo o padrão de testes efetuados a cada nova ferramenta do OOB, além das 404 tomografias reconstruídas no conjunto 1 (Basic CT-Scan Import) e das 151 na sessão 2 (AI CT-Scan Import), também procedeu-se com 115 para o sistema de 3 (AI Bones Landmarks), 101 para o sistema 4 (AI Soft Tissue Landmarks), e 101 para o sistema 5 (Frankfurt Align). Também foram efetuados 120 testes para o sistema unificado, com exceção do alinhamento dos dentes, além de 12 testes em três sistemas operacionais diferentes (12x3=36) com o sistema unificado completo. **Ao todo foram efetuados 1028 testes, visando analisar aspectos específicos do funcionamento das ferramentas em fases diferentes**.

Configuração da máquina: Processador Intel Core I9 9900K 3.6 GHZ/16M; 64 GB de memória RAM; GPU GeForce 8 GB GDDR6 256-bit RTX 2070; Placa mãe Gigabyte 1151 Z390; SSD SATA III 960 GB 2.5”; SSD SATA

[13] https://youtu.be/RRLIiqwSMKk

III 480 GB 2.5"; Water Cooler Masterliquid 240V; Linux Ubuntu 24.04 e Windows 11 (armazenados em mídias distintas).

Nos testes básicos chegou-se a uma taxa de 100% de sucesso nas reconstruções, desde que resolvidas as incompatibilidades das tomografias. O mesmo nível de sucesso se deu na segmentação por AI, já os testes com o posicionamento dos pontos, tanto nos ossos quanto nos tecidos moles, serviram para avaliar quais pontos eram mais constantes, de modo a utilizá-los para alinhamentos, poisicionamento de estruturas e limitação de áreas deformáveis. O teste do sistema unificado sem o alinhamento dos dentes serviu para avaliar se os pontos selecionados para o alinhamento em Frankfurt funcionariam em casos reais, resultanto em uma taxa de sucesso de 93,81% e uma média de tempo de 11 minutos e 10 segundos para cada processamento. Curiosamente, dos erros de alinhamento registrados, dois deles se deram por deformações ósseas nos pacientes e 4 ocorreram em tomografias médicas, indicando um melhor funcionamento em DICOMs advindos de CBCT.

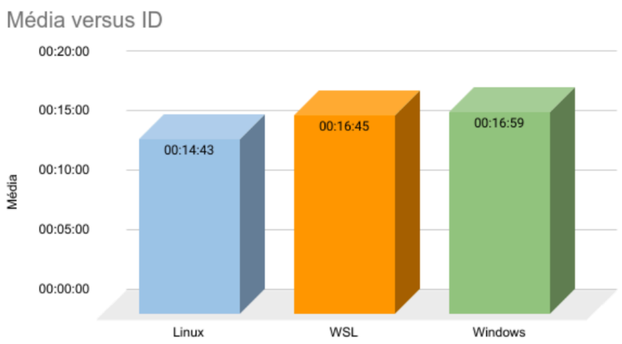


Figure2.13: Comparação entre sistemas diferentes.

Foram escolhidos os dados aleatórios de 12 pacientes anonimizados, com os quais foram rodados todos os passos do Sistema Unificado para a Criação de um Crânio Composto no OrtogOnBlender XP. Esse conjunto de 12 pacientes foi testado em três sistemas distindos, no Ubuntu Linux 24.04 rodando nativamente, no Windows 11 rodando nativamente e no Linux Ubuntu 24,04 rodando dentro do Windows 11 (WSL 2). Apesar de algumas pequenas diferenças estruturais e de adptações efetuadas para a compatibilização em cada sistema operacional, não houve grande diferença de resultados de tempo e aparência (Fig.2.12). O Linux se saiu ligeiramente melhor nos dois quesitos.

2.4 Conclusão

Em face aos resultados, alicerçados em tomografias de pessoas reais, em sua maioria com deformações faciais, o Sistema Unificado para a Criação de um Crânio Composto no OrtogOnBlender XP se mostrou suficientemente robusto e pronto para ser compartilhado com os seus usuários.

2.5 Agradecimentos

Ao Dr. William Sanchis, por ceder a tomografia computadorizada utilizada neste estudo. Um agradecimento especial a todos aqueles que enviaram tomografias computadorizadas, formando um grupo de arquivos importantíssimo para testar o uso do sistema em situações práticas.

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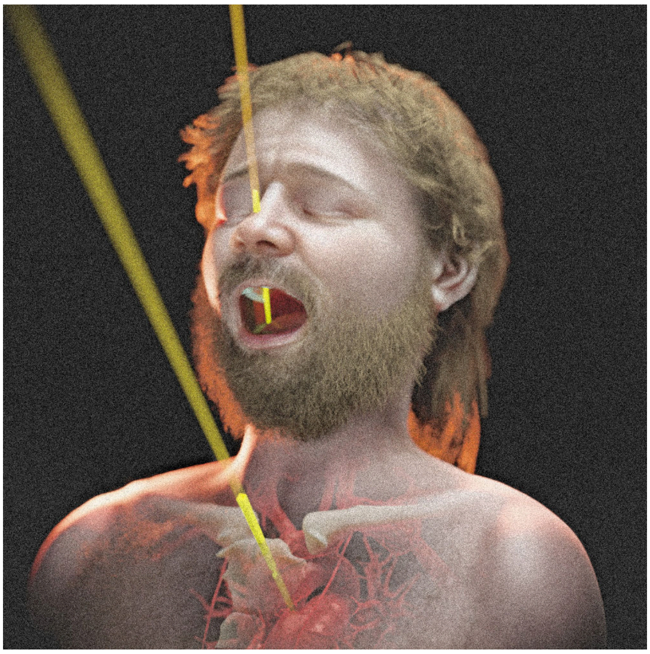
Chapter 3

A Aproximação Facial do Homem de Porsmose (ca. 5500 AP)



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DOI: 10.6084/m9.figshare.28207625

Warning: O presente trabalho é independente, sem vínculo com a instituição que guarda os restos mortais do Homem de Porsmose, tampouco com as universidades e instituições que os estudaram. O elemento motivador do capítulo é a criação de material didático para o ensino da técnica de aproximação facial, ao testar a possibilidade de se reconstruir uma face utilizando dados originalmente disponíveis em matérias de jornais, mídias online, livros e *journals* acadêmicos.

Attention: Caso encontre algum erro no texto, sinta-se à vontade para informá-lo aos autores, o contato pode ser feito via redes sociais acadêmicas disponíveis no início do capítulo.

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Google Scholar[14], ResearchGate[15], ORCID[16], Homepage.[17]

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3.1 Introdução

3.1.1 O Homem de Porsmose

Em agosto de 1946, durante os trabalhos de corte de turfa em Porsmose[18], o trabalhador Aksel Pedersen encontrou alguns ossos humanos com uma ponta de flecha transpassando uma das peças. Ele então notificou o Museu Nacional da Dinamarca, que posteriormente enviou os especialistas que escavaram e encontraram, a 2 metros de profundidade, várias partes dos esqueletos de duas pessoas [C_Becker_1952]. Um dos indivíduos seria um homem de 35-40 anos, com aproximadamente 1.66 m de altura, com biotipo compatível com a etnia nórdica, cujos restos ósseos apresentavam não

[14] https://scholar.google.com.br/citations?user=u33uvHUAAAAJ
[15] https://www.researchgate.net/profile/Cicero-Moraes
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[17] http://www.ciceromoraes.com.br

[18] https://www.kulturarv.dk/fundogfortidsminder/Kort?bbox=679270.589551776,6125972.95828739,685950.589551776,6132652.95828739&point=682610.589551776,6129312.95828739

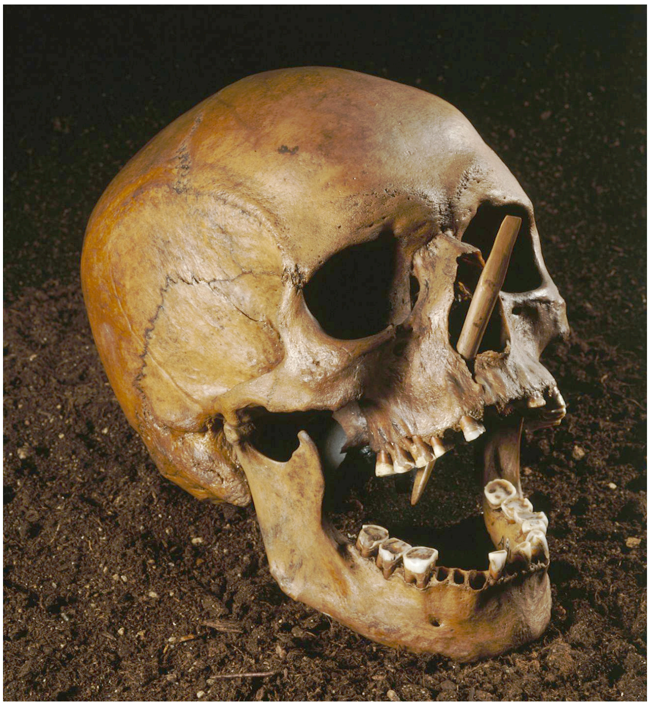

Figure3.1: Skull from Porsmose - Lennart Larsen - Wikimedia Commons (https://commons.wikimedia.org/wiki/File:Porsmose_DO-1229.jpg). A imagem foi recortada e clareada.

Figure3.2: Porsmose-Mans Breastbone - Bullenwächter - Wikimedia Commons (https://commons.wikimedia.org/wiki/File:Porsmose-Mans_Breastbone.jpg). A imagem foi recortada e clareada.

uma, mas duas pontas de flechas atravessando estruturas ósseas; uma com 106 mm que atingiu a narina direita e o palato (Fig.3.1) e outra de 127 mm na região do esterno e que teria atingido grandes troncos arteriais, podendo assim ter causado uma morte bastante rápida (Fig.3.2) [C_Becker_1952].

Os estudos iniciais indicaram que o Homem de Porsmose teria sido assassinato no período Neolítico [C_Becker_1952], além disso as pontas de flecha de osso, uma quadrada e outra circular, se enquadram em culturas neolíticas estudadas posteriormente [C_Iversen_2016]. Datações de restos pertencentes a chamada cultura Funnelbeaker (TBK), permitiram o posicionamento temporal do Homem de Porsmose em aproximadamente 3500 BCE, ou há ~5500 anos atrás [C_Nielsen_2018].

3.1.2 A Motivação para o Projeto de Aproximação Facial

As ferramentas de aproximação facial e de outras partes da anatomia permitem não apenas que se tenha ideia da aparência de indivíduos durante a vida, como oferecem a possibilidade de se comparar estruturas anatômicas, bem como a dinâmica de acidentes. Exemplos de projetos envolvendo alguns dos autores do presente estudo ilustram tal abordagem, como o caso da múmia egípcia com macrencefalia, cujo estudo permitiu entender o motivo do uso de um caixão incompatível com a idade do jovem, bem como o comprometimento da máscara funerária, muito provavelemente por problemas de adequação estrutural ao não permitir o fechamento do caixão com a posição esperada da peça [C_Moraes_et_al_2024]. Outros projetos que podem ser citados remetem a, uma vítima da batalha de Gotland de 1321, que recebeu um golpe de um objeto perfuro cortante na face [C_Moraes_et_al_2022], o caso do rei egipcio Seqenenre Taa II que teria recebido vários golpes de espada ou machados no rosto [C_Moraes_and_Habicht_2024] ou mesmo de Phineas Gage, que teve o seu crânio transpassado por uma barra de ferro e sobreviveu ao acidente [C_Moraes_2024]. Em todos os casos as ferramentas de computação gráfica, tangenciando áreas de museologia e da medicina, permitiam a criação de ferramentas didáticas para uma melhor compreensão e, indiretamente, um debate sobre os ocorridos, envolvendo especialistas e o público em geral. Ao tomarem conhecimento da história do Homem de Porsmose e, uma vez que imagens sob licença Creative Commons dos restos mortais estão disponíveis para servirem como referência de reconstrução estrutural, os autores se mobilizaram para não apenas apresentarem uma face aproximada, mas também um estudo para estimar as regiões anatomicas possivelmente afetadas pela ponta de flecha fatal.

Attention: É importante salientar que, além dos projetos supracitados, envolvendo casos históricos e arqueológicos, alguns dos autores também atuaram ou atuam no campo forense junto à equipes policiais brasileiras. Tanto no caso de aproximação facial forense [C_Baldasso_et_al_2020] quanto no estudo da dinâmica e reconstrução de cenas de crimes[19].

3.2 Materiais e Métodos

O presente trabalho foi efetuado utilizando apenas software livre e de código aberto. A modelagem 3D teve como base o software Blender (https://www.blender.org/), rodando o add-on OrtogOnBlender (https://www.ciceromoraes.com.br/doc/pt_br/OrtogOnBlender/index.html), que fornece ao sistema ferramentas de reconstrução de tomografias computadorizadas, bem como de aproximação facial forense. A edição de imagem foi efetuada no software The Gimp (https://www.gimp.org/) e Inkscape (https://inkscape.org/), todos sob o sistema Ubuntu Linux 24.04 (https://ubuntu.com/).

Figure3.3: Reconstrução do crânio em duas etapas, utilizando como referência imagens com licença livre disponíveis na Wikimedia Commons. Á esquerda (Andreas Franzkowiak https://commons.wikimedia.org/wiki/File:Porsmose-Man.jpg) e à direita (Lennart Larsen https://commons.wikimedia.org/wiki/File:Porsmose_DO-1229.jpg).

Para a modelagem do crânio, recorreu-se a um conjunto de fotografias da peça, dosponíveis sob licença Creative Commmons no portal Wikimedia Commons[20]. Tais imagens foram ajustadas ao background de crâmeras distintas, que eram posicionadas na cena tendo como base o crânio de um doador virtual. Esse crânio foi ajustado (deformado) aos poucos, até que a sua estrutura se compatiblizasse com a do Homem de Porsmose (Fig.3.3 A e B). O crânio do doador digital utilizado era completo, mas em baixa resolução, pois o objetivo era o de criar uma estrutura compatível, mas contendo todos os dentes, diferente do crânio base com estruturas ausentes. Para a geração do modelo de referência final, o crânio de outro doador virtual foi reconstruído com ferramentas de segmentação específicas que separaram as peças anatômicas: crânio, mandíbula, arco superior e arco inferior [C_Moraes_et_al_2024b]. Assim foi possível ajustar o doador virtual ao crânio do Homem de Porsmose com detalhes mais compatíveis aos da peça original (Fig.3.3 C e D). O parâmetro de escala foi ajustado a partir da modelagem da ponta de flecha, com a conhecida dimensão de 107 mm. Tal técnica de reconstrução do crânio a partir da fotografia ou ilustraçãoes já foram utilizadas por membros da equipe atual em outros projetos como a aproximação facial de Tutancâmon [C_Moraes_et_al_2023] e de Amenhotep III [C_Moraes_et_al_2024c].

[19] https://bit.ly/3BHCKCw
[20] https://commons.wikimedia.org/w/index.php?search=Porsmose&title=Special:MediaSearch&go=Go&type=image

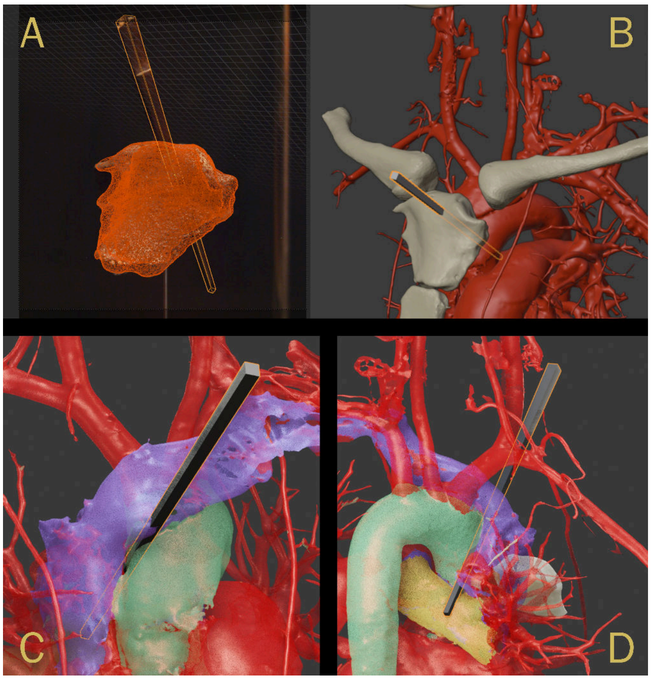

Figure3.4: Reconstrução do esterno a partir de um doador digital, sobre fotografia disponível na Wikmedia Commons (Bullenwächter https://commons.wikimedia.org/wiki/File:Porsmose-Mans_Breastbone.jpg).

Para a reconstrução do esterno recorreu-se a outra tomografia, de um doador virtual contemplando aquela região, bem como o sistema circulatório. Inicialmente o esterno do doador foi ajustado ao volume do Homem de Porsmose, além da modelagem da ponta de flecha que forneceu o parâmetro de escala (127 mm) (Fig.3.4 A), portanto, toda a estrutura reconstruída, além de estar dentro dos parâmetros da volumetria, também respeitaram a escala real. Com o esterno reconstrído e com os dados da ponta de flecha junto a reconstrução das demais estruturas anatômicas (Fig.3.4 B), foi possível observar, guardadas as limitações da técnicas e da margem de erro, que foram acometidas a veia braquiocefálica esquerda (em roxo), o arco da aorta (em verde) e a artéria pulmonar direita (em amarelo) (Fig.3.4 C e D) [C_Tank_and_Gest_2009].

Com o crânio tendo sua anatomia estimada pelo processo descrito, foi possível efetuar uma série de projeções de estruturas anatômicas, tanto do rosto quanto do crânio, avaliar a coerência anatômica frente a

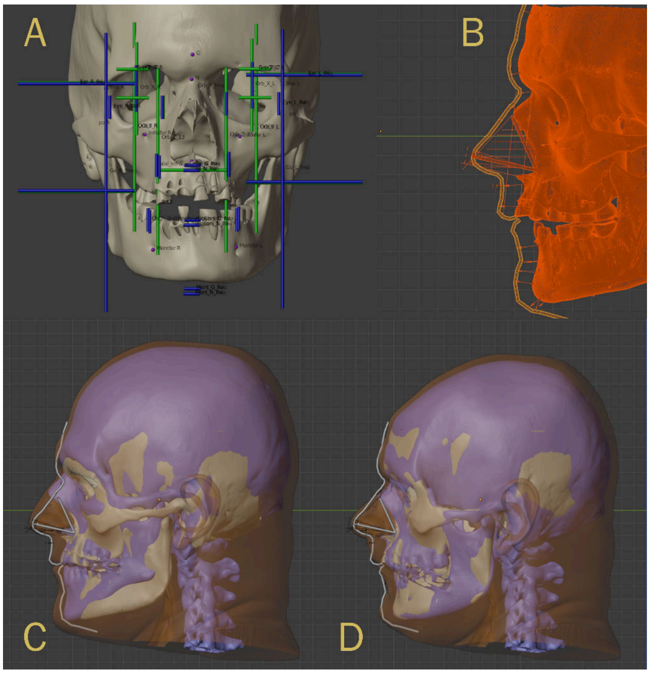

Figure3.5: Etapas iniciais da aproximação facial.

essas projeções e ter à disposição dados acerca do posicionamento dos globos oculares, orelhas, boca, nariz e outros (Fig.3.5 A). Tais projeções utilizam como referência mensurações efetuadas em tomografias de pessoas vivas, de ancestralidades diversas [C_Moraes_and_Suharschi_2022]. Duas videoaulas sobre as projeções estruturais estão disponíveis em: aula 1[21], aula 2[22]. Para o traçado do perfil (Fig.3.5 B) recorreu-se a dados de tabela de espessura de tecidos moles de um europeu genérico com a faixa etária de 30-39 anos [C_De_Greef_2006], além da projeção nasal complementar baseada em [C_Moraes_et_al_2021] [C_Moraes_and_Suharschi_2022]. Uma videoaula sobre a projeção nasal pode ser assistida de modo online[23]. Um elemento reforçador de coerência estrutural utilizado foi a técnica de deformação anatômica [C_Quatrehomme_et_al_1997], que consiste em importar a cabeça de um doador digital e ajustar a estrutura de modo que o crânio do doador se compatibilize ao do indivíduo a ser aproximado (Homem de Porsmose), refletindo a deformação no tecido mole e resultando em uma face compatível com aquela em vida (Fig.3.5 C e D). Uma videoaula sobre o processo de deformação anatômica está disponível de modo online_[24].

O busto básico final utilizou as informações de todas as projeções supra mensionadas, compatibilizando-se com as medidas esperadas para a face, dentro dos limites estipulados por técnicas diferentes (Fig.3.6 A e B). Como se trata de um trabalho voltado para apresentação didática e não forense, criou-se uma face final com elementos especutalivos, como barba, cabelos e olhos pigmentados, utilizando uma coloração genérica

[21] https://youtu.be/U6oYkEmfyWo
[22] https://youtu.be/Vcz2e5uSFX8
[23] https://youtu.be/F205kLQ--Oo
[24] https://youtu.be/xig5_EcIFWA

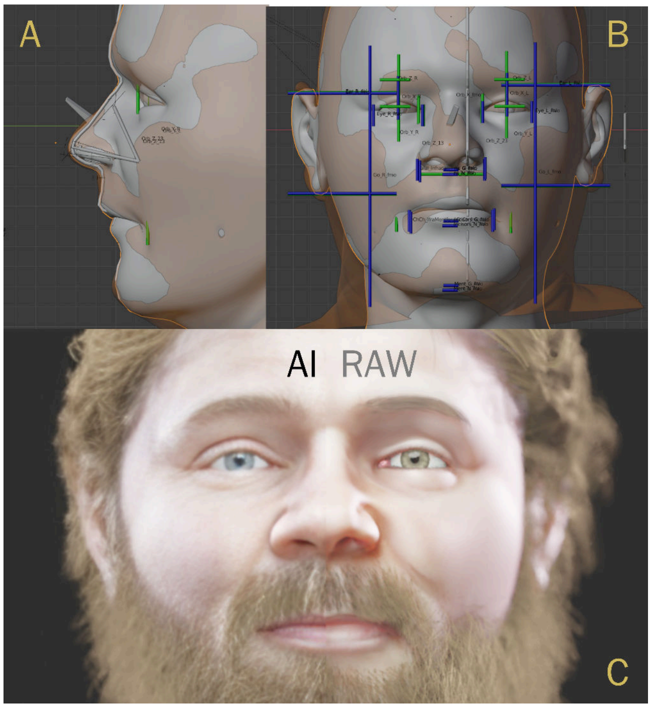

Figure3.6: Etapas finais da aproximação facial.

extraída do cruzamento de imagens encontradas em sites de busca a partir do termo “Danish man face”, mais detalhes sobre a abordagem podem ser vistos em [C_Moraes_et_al_2024d]. As imagens da face final passaram por um aguçamento de detalhes a partir de inteligência artificial (Fig.3.6 C), utilizando a solução de código aberto Codeformer [C_Zhou_et_al_2022]. Embora a ferramenta de inteligência artificial tenha apresentado bons resultados, foram necessárias edições complementares no software The Gimp para corrigir problemas estruturais nas imagens finais.

3.3 Resultados e Discussão

Foram renderizadas várias imagens didáticas buscando apresentar os resultados do atual projeto.

Uma vista frontal neutra permite aos interessados visualizarem o rosto do Homem de Porsmose (Fig.3.7). Uma versão contendo as flechas ilustram a posição das mesmas, com a cabeça no plano de Frankfurt (Fig.3.8). Para evidenciar a gravidade do ferimento na região do esterno três imagens foram criadas, contendo a anatomia interna (Fig.3.9, Fig.3.10, Fig.3.11), nelas é possível visualizar quanto a ponta da flecha penetrou no sistema circulatório e como as estruturas das flechas, quando observadas nas vistas frontais e de perfil não destoam significativamente os seus ângulos.

Dada a complexidade estrutural, as imagens da seção Materiais e Métodos são essenciais para que um observador mais interessado nos detalhes compreenda quais as estruturas podem ter sofrido lesão. Pensando nisso uma imagem didática foi criada para ilustrar a potencial gravidade dos ferimentos provocados pela ponta de flecha que golpeou a região do esterno (Fig.3.12).

Figure3.7: Busto colorido final, neutro - vista frontal com ângulo de captura fechado.

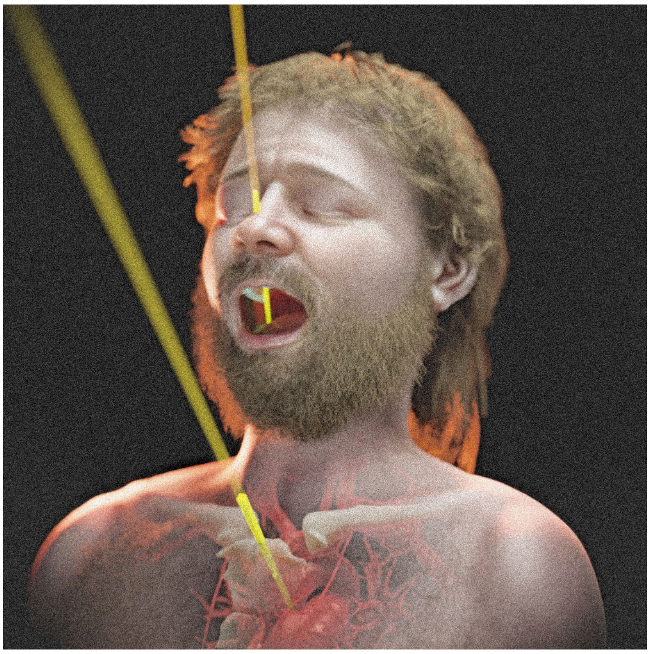

Figure3.9: Busto didático completo, com elementos anatômicos - vista lateral.

Figure3.8: Busto opaco com a estrutura completa das flechas - vista lateral.

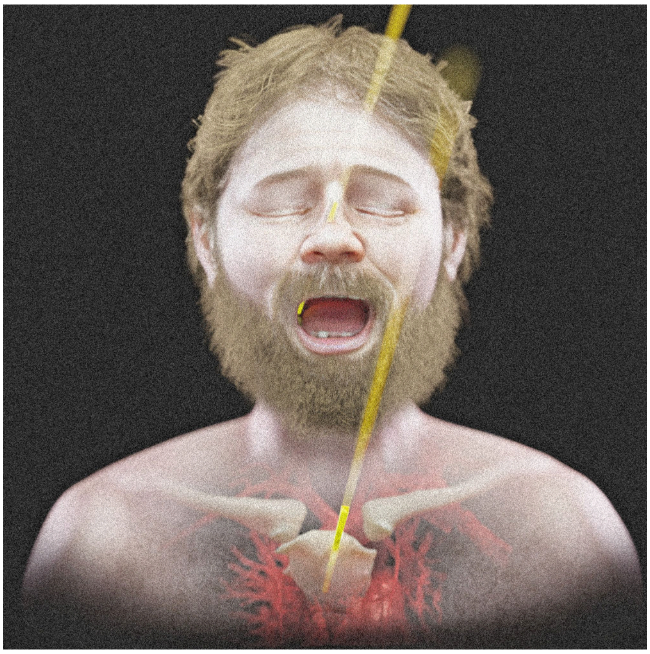

Figure3.10: Busto didático completo, com elementos anatômicos - vista frontal.

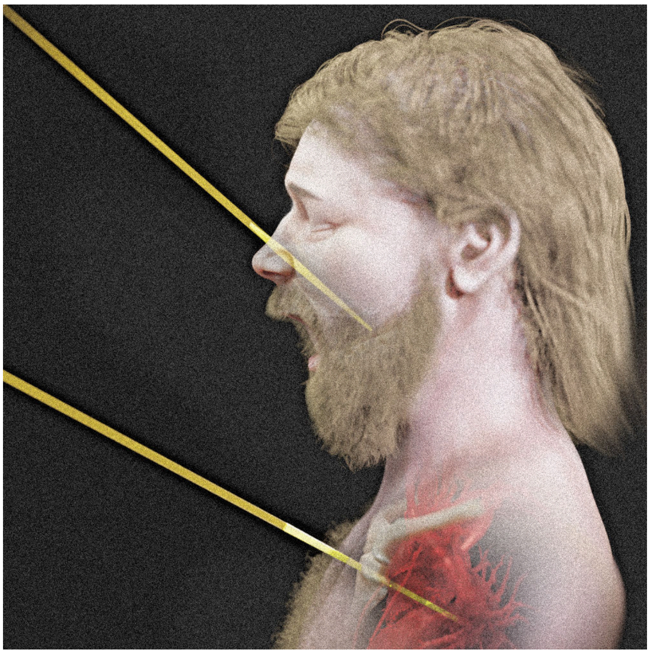

Figure3.11: Busto didático completo, com elementos anatômicos - vista de perfil.

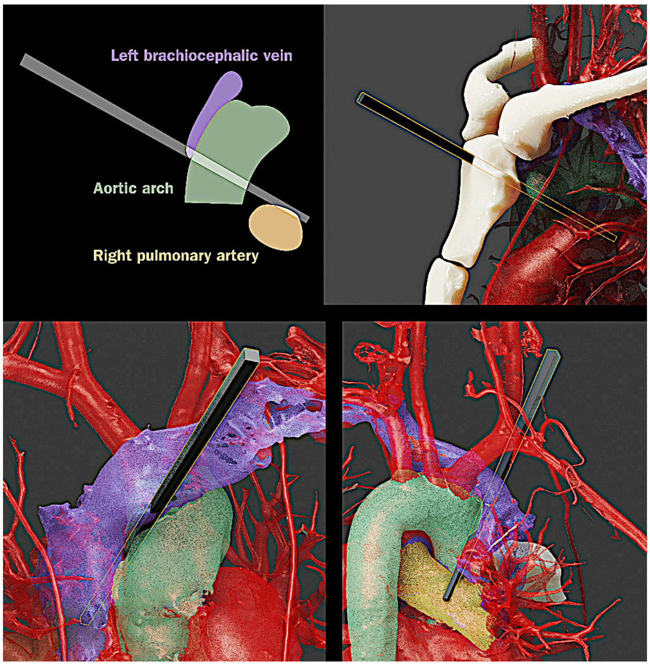

Figure3.12: Imagem didática da ponta da flecha na região do esterno.

3.4 Agradecimentos

À equipe do Museu Nacional da Dinamarca (https://en.natmus.dk/), que gentil e prontamente respondeu aos nossos e-mails fornecendo importante literatura, utilizada para a composição desde documento. À Dra. Paola Corso, por ceder a tomografia utilizada na reconstrução da anatomia do peito e ao Dr. Richard Gravalos por ceder a tomografia utilizada na deformação anatômica facial.

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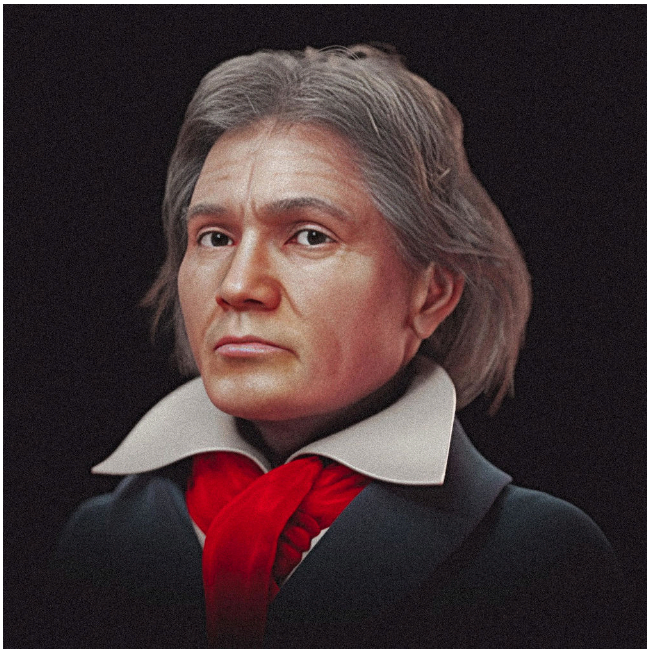
Chapter 4

Beethoven from a New Perspective: Forensic Facial Approximation, Anthropometry, High Abilities, and Genius



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Google Scholar[25], ResearchGate[26], ORCID[27], Homepage.[28]

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Important: The online version of this study can be accessed at: https://ortogonline.com/doc/pt_br/OrtogOnLineMag/11/Beethoven.html

Abstract

This study presents an interdisciplinary approach to explore the life and legacy of Ludwig van Beethoven, one of the greatest composers in history. Using forensic facial approximation techniques, a three-dimensional reconstruction of the composer's face was created based on historical photographs of his skull, with authorization kindly granted by the Beethoven-Haus Bonn, introducing a new perspective on the visualization of historical figures. This work also marks the first documented measurement of the composer's cranial capacity and head circumference. Additionally, it presents the first rigorous meta-analysis of his height, based on bone measurements from the 1863 exhumation, improving previous estimates with greater methodological precision. Complementarily, this article proposes the first systematic academic analysis of Beethoven's intelligence and genius, integrating historiometry and contemporary concepts of high abilities/giftedness. This approach not only sheds light on the impact of his work but also contextualizes the personal challenges, such as progressive deafness, that shaped his artistic production. By combining forensic science, anthropometry, and psychology, this study offers a unique perspective on Beethoven's complexity, highlighting his resilience, creativity, and a legacy that continues to inspire generations.

Keywords: *Forensic facial approximation, Anthropometry, Cranial capacity, High abilities, Genius, Beethoven*

Attention: Should you encounter any errors in the text, kindly report them to the author; he may be contacted through the academic social media platforms mentioned at the beginning of the chapter.

[25] https://scholar.google.com.br/citations?user=u33uvHUAAAAJ
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4.1 Introduction

4.1.1 A Brief Biography

Beethoven's life, filled with emotional highs and lows, was intensely turbulent, reflected both in his music and his personal relationships. This narrative, based on Fauconnier (2013) [Faucconier_2013_d], seeks to avoid the hagiography adopted by many biographers, who idealized Beethoven as an untouchable hero, and instead opts for a more human approach, highlighting his struggles and achievements without romanticizing them. For a more comprehensive understanding, it is recommended to consult other authors who may offer complementary perspectives on the composer's complex journey.

Ludwig van Beethoven, the grandfather (1712–1773), was a musician from Flanders (present-day Belgium) who moved to Bonn in 1732, then part of the Electorate of Cologne, a state of the Holy Roman Empire (now part of Germany). In Bonn, he distinguished himself as a musician in the local court chapel and later became Kapellmeister. To supplement his income, he also managed a small wine trade, which helped support his family. Of his children, probably only one, Johann van Beethoven, survived to adulthood. Ludwig, the grandfather, dedicated himself to passing on his musical knowledge to his son.

Johann van Beethoven, though talented, faced personal difficulties, including struggles with alcoholism. He married Maria Magdalena Keverich, a union that, though initially disapproved of by some due to Maria's social circumstances, resulted in a family. Of their children, three survived to adulthood, with Ludwig van Beethoven, baptized on December 17, 1770, in Bonn, being the eldest of the surviving brothers but the second child of his parents, named after his grandfather.

Johann recognized Ludwig's exceptional musical talent early on and sought to promote him as a prodigy, inspired by the success of Wolfgang Amadeus Mozart. To further highlight his son's abilities, Johann even presented Ludwig as younger than he actually was, a common practice at the time to emphasize precocity. This age discrepancy was later discovered by Beethoven around 1810. From a young age, Ludwig van Beethoven displayed traits of an intense personality, later described as impetuous, characteristics that would become defining in adulthood. The musical training imposed by his father, Johann, who struggled with alcoholism, was rigorous and often exhausting. There are accounts of an episode where Johann and a fellow musician woke Ludwig at night for piano lessons, bringing him to tears—a rare practice that reflected the pressure placed on the young boy. Despite the demanding and sometimes detrimental routine to the family's emotional well-being, Beethoven's musical abilities did not go unnoticed. He developed a genuine passion for music, excelling as a pianist and organist and composing his first works as a teenager. The death of his mother, Maria Magdalena, in 1787 deeply affected him, and Johann's erratic behavior forced Beethoven, at the age of 18, to take on the responsibility of head of the family in Bonn. His talent impressed Christian Gottlob Neefe, his main teacher, who encouraged him to refine his techniques and introduced him to the local music scene. It was Neefe who proposed that the city fund Beethoven's trip to Vienna, the main musical center of Europe at the time, to further his studies and career.

Beethoven left Bonn for Vienna in November 1792, and his father, Johann, died shortly after in December 1792, where he quickly distinguished himself as a piano virtuoso, earning the admiration of the local nobility, who soon began to sponsor him. There, amidst moments of great joy and ardent, often unrequited, passions that deeply marked his life, the composer carried the scars of his losses, particularly that of his mother in 1787. His brothers, Kaspar Anton Karl and Nikolaus Johann, joined him in Vienna, where they sometimes became a source of emotional tension. With an intense personality, Beethoven alternated between bouts of frustration and moments of deep tenderness toward his brothers, often driven by a mix of irritation and regret.

His reputation as a piano virtuoso and innovative composer led him to study under Joseph Haydn, with whom he honed his compositional techniques. His intense personality and unique style attracted influential patrons, such as Prince Lichnowsky, who provided financial support. He quickly gained recognition with works such as the Piano Sonatas, Op. 2 (1795), dedicated to Haydn, which revealed his harmonic boldness, and the First Piano Concerto (1795, revised in 1800), which solidified his fame as a soloist. His Dressler Variations and Piano Trios, Op. 1 (1795), also impressed with their originality. Around 1798, Beethoven began to notice the first signs of deafness, a condition he initially tried to conceal but which caused him anguish and marked a turning point in his life and work. Despite this, he continued to compose with vigor, producing the Pathétique Sonata, Op. 13 (1799), a masterpiece that combined profound emotion and structural innovation, signaling the genius that would define his career.

By around 1800, with his deafness worsening, Beethoven faced a challenge that deeply shook him both emotionally and professionally. In letters, such as the Heiligenstadt Testament of 1802, he expressed the anguish of progressively losing his hearing, fearing its impact on his career and social life. Nevertheless, this period was one of immense creativity, producing masterpieces like Symphony No. 3, "Eroica" (1804), which revolutionized the symphonic genre with its scale and emotion, and the Moonlight Sonata, Op. 27 No. 2 (1801), marked by its lyrical intensity. His often unrequited passions, such as his affection for Giulietta Guicciardi, to whom he dedicated the Moonlight Sonata, imbued his music with unique emotional depth, though they also brought personal suffering.

Symphony No. 5 (1808), with its iconic opening motif, and Symphony No. 6, "Pastoral" (1808), reflecting his connection to nature, solidified his genius amidst auditory adversity.

The death of his brother Kaspar Anton Karl in 1815 dealt another blow to his life. Kaspar, who had moved to Vienna with Beethoven, left behind a son, Karl, and his widow, Johanna, with whom Beethoven entered a prolonged and bitter legal dispute over the custody of his nephew. He considered Johanna unfit to raise Karl, and his intense personality drove him to fight relentlessly, culminating in a legal battle that extended until 1820. During this period, Beethoven's deafness worsened significantly, further isolating him and intensifying his introspection. Yet, his musical output remained extraordinary, with works like the Piano Sonatas, Op. 101 (1816) and Op. 106, "Hammerklavier" (1818), which challenged the conventions of the time with their complexity and depth. These compositions reflected both his inner struggles and his ability to transcend limitations, solidifying his reputation as one of the greatest composers of his era.

In his final years, Beethoven faced a period of intense personal and artistic turmoil, marked by the progressive deterioration of his health and the worsening of his deafness, which isolated him almost completely. The legal battle for custody of his nephew Karl, initiated after Kaspar's death in 1815, concluded in 1820 when Beethoven gained sole custody. However, his relationship with Karl was troubled: his intense personality and attempts to shape the young man led to conflicts, culminating in Karl's attempt to take his own life in 1826, an event that deeply shook the composer. Karl returned to Beethoven in 1827, shortly before the composer's death, in a moment of reconciliation that brought some comfort to Beethoven on his deathbed. Despite these adversities, Beethoven reached one of the peaks of his career with Symphony No. 9, "Choral" (1824), a monumental work that introduced voices to the symphonic genre with Schiller's "Ode to Joy," expressing a vision of universal brotherhood that transcended his personal struggles. Other late works, such as the String Quartets, Opp. 127, 130, 131, 132, and 135 (1825–1826), revealed profound introspection and radical innovation, cementing his genius amidst a life marked by passions, losses, and challenges.

Beethoven's emotional highs and lows profoundly shaped his life, with moments of despair so intense that he contemplated ending his own life, as revealed in the Heiligenstadt Testament of 1802, where he expressed his anguish over his progressive deafness. Ironically, the loss of hearing—a personal tragedy for a musician—seemed to fuel his creativity even further, resulting in works of universal value that continue to resonate today. Lacking physical attractiveness, often described as clumsy and rough in appearance, Beethoven also did not truly belong to the nobility, though he moved in their circles due to the recognition of his talent. He faced numerous rejections in his passionate pursuits and marriage proposals, experiences that, far from silencing him, seemed to further stimulate his need to create. The bitter irony of being rejected in love and deprived of the sense that defined his profession only intensified the creative force that drove him. His tempestuous and often antisocial personality was reflected in his unkempt appearance and disorganized, often dirty apartments, which sometimes shocked visitors. Nevertheless, Beethoven found ways to adapt to the singularities of his mind, channeling his emotional intensity into profoundly innovative compositions. Living on the margins of social conventions, between introspection and bursts of passion, he became a central figure in the history of music—a genius whose art transcended the limitations imposed by his tumultuous existence.

4.1.2 From Autopsy to Exhumation of 1863

Following Beethoven's death on March 26, 1827, his body underwent a detailed post-mortem examination. During the autopsy, incisions were made in the composer's skull, and parts of his cranial vault were removed. This practice, common at the time for anatomical studies and to determine the cause of death, resulted in the extraction and subsequent retention of skull fragments. The autopsy process lasted a few hours, and the remains were then prepared for burial. Beethoven's funeral, held on March 29, 1827, was a grand event. Despite the invasive post-mortem treatment, the respect and admiration for the composer were immense. It is estimated that around 20,000 people attended the ceremony in Vienna, paying their final respects to one of the greatest figures in classical music [Meredith_2005_d].

In 1863, Ludwig van Beethoven's remains were exhumed from their original resting place in Vienna's Währing Cemetery. This was not a routine exhumation; it was driven by the desire to preserve the remains of two of Vienna's greatest composers, Beethoven and Schubert, who were buried near each other in a cemetery that was already in disuse and known to be in poor condition. The primary goal was to transfer them to a safer location, with the intention of future relocation to an "honorary cemetery." The exhumation was meticulously documented, with prominent figures present, including doctors, anatomists, and members of the Gesellschaft der Musikfreunde (Society of Friends of Music). One of the key findings was the condition of Beethoven's skull. Due to the 1827 autopsy, the skull was not intact; significant fragments of the cranial vault had been removed and retained by physicians at the time. During the 1863 exhumation, the skull was carefully examined, and the absence of these parts was noted and documented, confirming the earlier post-mortem interventions. In addition to the skull, Beethoven's skeletal remains were carefully lifted and examined. Measurements of the limb bones were taken, and the composer's height was estimated [Meredith_2005_d].

Analysis of Beethoven's skull revealed a notable asymmetry in the cranial vault. It was observed that the left side was distinctly larger than the right. To facilitate study and photographic documentation of these fragments, they were carefully assembled, with clay used to fill gaps and reconstruct the general shape of the skull for visualization purposes [Reiter_2022_d]. Johann Batta Rottmayer photographed the skulls of Beethoven and Schubert in 1863. These photographs were taken on two separate dates: Friday, October 16, and Tuesday, October 20. The images were captured from both frontal and lateral perspectives [Meredith_2005_d].

4.1.3 Facial Approximation in 2025

The author has performed facial approximations of over 100 historical figures throughout their career, many at the request of museums, law enforcement agencies, and other organizations. Recently, their work has focused on two main areas: the development of 3D digital approaches for teaching forensic facial approximation and the analysis of points of interest related to the individual being reconstructed. Regarding the facial approximation technique, a study published in 2025 involving the alleged skull of Mozart [Moraes_et_al_2025_d] demonstrated that it was possible to reconstruct the face with high accuracy using photographs. During research on the Austrian composer's skull, references to Beethoven's skull frequently arose, which inspired the development of the present project. This project also investigates, through historical analysis, the possible high abilities/giftedness associated with the composer's alleged genius. In May 2025, the author accessed photographs of the skull from the Digital Archive of the Beethoven-Haus Bonn (www.beethoven.de), having requested and received authorization from the institution to ensure compliance with its policies, which formed the basis for this work. The goal, consistent with the author's usual research practice, is to present a preprint version of the article, followed by submission for peer review, as done in previous projects published in this same technical-scientific journal.

4.2 Materials and Methods

4.2.1 Forensic Facial Approximation

Forensic facial approximation is a facial recognition technique where an individual's face is reconstructed or approximated from a skull. The goal is to achieve initial recognition by an acquaintance or family member. If positive, this can lead to subsequent identification in police cases involving crimes [Baldasso_et_al_2020_d]. For historical skulls, as in this study, the technique aims to humanize mortal remains for presentation in academic publications, general media, or museum settings.

As mentioned, this work requires a skull for facial approximation. The skull is then digitized, either by computed tomography [Abdullah_et_al_2022_d], by photogrammetry [Baldasso_et_al_2020_d], or by modeling from a photograph [Moraes_et_al_2025_d], which was the chosen method for this study.

The initial reconstruction was based on three photographs, authorized for use by the Beethoven-Haus Bonn (https://www.beethoven.de/):

- **B 743/a** - *Beethovens Schädel - Reprofotografie einer Aufnahme von Johann Batta Rottmayer* (https://www.beethoven.de/en/media/view/6461181120217088/scan/0) - a frontal photograph of the skull.
- **NE 303 b** - *Beethovens Schädel - Fotografie von Johann Batta Rottmayer, Wien, 1863, späterer Abzug, nach 1863* (https://www.beethoven.de/en/media/view/6501393154179072/scan/0) - a corrected frontal version, without the large structural deformation on the right side of the skull.
- **NE 262 c, 2** - *Beethovens Schädel im Profil - Fotografie von Johann Batta Rottmayer, Wien, 1863* (https://www.beethoven.de/en/media/view/5173612705218560/scan/0) - a lateral photograph of the skull.

The entire process used free, open-source, and cross-platform software: Inkscape for vector graphics (https://inkscape.org/), Gimp for image correction and editing (https://www.gimp.org/), and Blender for 3D modeling (https://www.blender.org/). The OrtogOnBlender add-on (https://www.ciceromoraes.com.br/doc/pt_br/OrtogOnBlender/index.html) was run to expand Blender's capabilities for tasks not available natively, such as computed tomography reconstruction, photogrammetry, and forensic facial approximation tools.

Using the two frontal images and the lateral image, it was possible to draw two two-dimensional skull outlines, corresponding to the frontal view (X and Z axes) and lateral view (Y and Z axes), encompassing the data in 3 dimensions (Fig.4.1, A). These projections allow for modeling a structure based on proportion, but not to the correct scale. This was resolved with measurements taken from the skull reassembled in 1888 [Anthropologische_1888_d]. For skull modeling, the anatomical deformation technique was used, where a virtual donor's CT scan is imported into the scene and the head is adjusted according to the reference—in this case, the two two-dimensional drawings of Beethoven's skull (Fig.4.1, B). The focus of the deformation or adjustment is to convert the donor skull into Beethoven's skull, causing the soft tissue to reflect these adjustments and thereby providing a facial reference (Fig.4.1, C). Another approach is used for facial projection: initially, a series of soft tissue thickness markers, based on a group of living Europeans measured by ultrasound [De_Greef_2006_d], are positioned along the

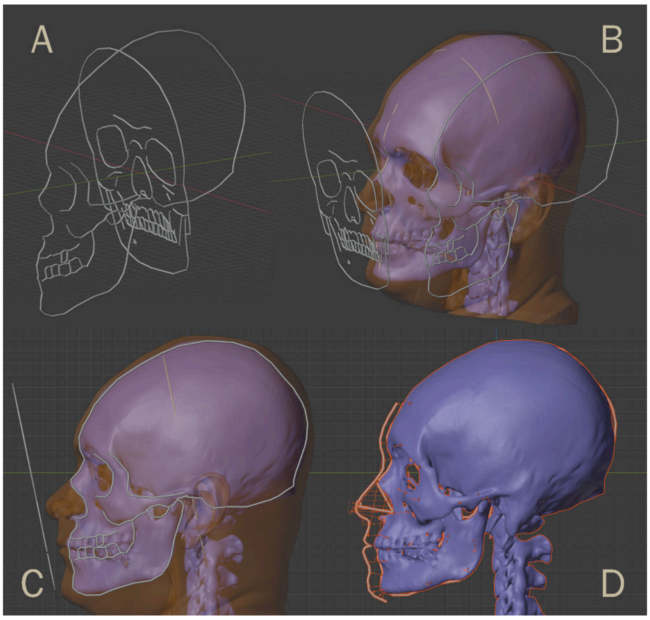

Figure4.1: Initial steps of facial approximation.

resulting skull, providing boundaries for the soft tissue. Next, nasal projection is performed, based on measurements taken from CT scans of living individuals [Abdullah_et_al_2022_d]. This, along with the soft tissue thickness markers, provides the basis for tracing the facial profile (Fig.4.1, D).

The profile tracing proved compatible with the face resulting from anatomical deformation, with a slight difference in the chin area (Fig.4.2, A). To further complement the facial approximation data, anatomical points are positioned on the skull, and an automatic projection of soft tissue and bone structures is made, based on measurements from CT scans of living individuals [Abdullah_et_al_2022_d] (Fig.4.2, B). The basic face is the result of interpolating all previous projections (anatomical deformation, profile tracing, and structural projections of the skull and soft tissue) (Fig.4.2, C). The bust is then detailed with expression lines to match the 50+ age group, along with clothing based on Joseph Karl Stieler's famous painting from 1820 (https://commons.wikimedia.org/wiki/File:Beethoven.jpg) (Fig.4.2, D). The scene receives digital lighting, and colors are adjusted, as are the graying hairs (Fig.4.2, E). The final step of facial approximation involves enhancing facial details with the artificial intelligence (AI) tool Codeformer [Zhou_et_al_2022_d], integrated into the new (and still publicly unavailable) version of the add-on, named OrtogOnBlender XP. The tool's weight is set to 1.0 to maintain the original structure's form, not influencing the face's structure, but minimally improving details (Fig.4.2, F).

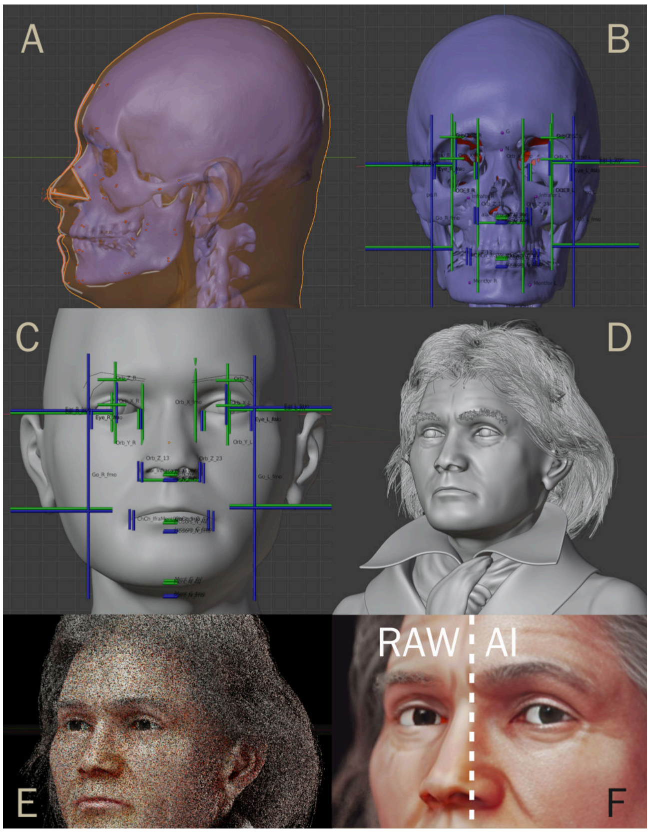

Figure4.2: Final steps of facial approximation.

4.2.2 Anthropometric Measurements

In anthropometric studies, it's common to estimate the height of the individual being analyzed. Biographical descriptions consulted indicate that Beethoven was a relatively short person, described as "shorter than average stature" in one account [Faucconier_2013_d]. This information is partially corroborated by a study that estimated his height at 1.65 m [Kubba_and_Young_1996_d]. However, that publication does not detail the methodology used to arrive at this value, which opens room for a more in-depth investigation in this work. One approach to estimating an individual's height involves equations based on bone measurements. Fortunately, there are records of examinations performed on Beethoven's remains during his first exhumation in 1863 [Heifert_1863_d], which provide the following metric measurements: ~41.28 cm for the femur, ~33.02 cm for the tibia, and ~30.40 cm for the humerus. With this data, a meta-analysis can be performed using formulas from six authors, available in two studies [Boldsen_1984_d] [Trotter_and_Gleser_1952_d], covering 13 distinct projections based on the femur, tibia, and humerus.

Another relevant measurement, endocranial volume, appears to be rarely or never addressed in academic publications. By leveraging the skull reconstruction, with the application of anatomical deformation and endocranial segmentation techniques, in addition to conversion to brain volume [Moraes_et_al_2023_d] [Moraes_et_al_2025_d], it will be possible to estimate a rarely explored value. Head circumference, useful in assessing normality patterns, will also be considered.

4.2.3 High Abilities/Giftedness and Genius

Beethoven is frequently recognized as a genius [Faucconier_2013_d] [Kubba_and_Young_1996_d] [Kauffman-Ortega_and_Diaz_2020_d], consistently appearing on lists of humanity's greatest intellects (https://www.toptenz.net/10-great-minds-throughout-history.php). However, the condition of genius, though notable, may lack consistent psychometric or academic foundation. This study seeks to address the composer's potential IQ [Cox_1926_d] and characteristics associated with genius, as described in works published by academics [Davidson_2017_d] [Simonton_2009_d].

4.3 Results and Discussion

4.3.1 Forensic Facial Approximation

Three groups of images related to facial approximation were generated:

- **Basic and objective**: This group contains only simple, grayscale structures, without details like expression lines or texturing, focusing on the fundamental elements of the face. This is the most consistent result that the facial approximation technique can offer. However, while more precise and satisfying for forensic specialists, it's not usually widely appreciated by the general public, as it lacks broader humanization (Fig.4.3).

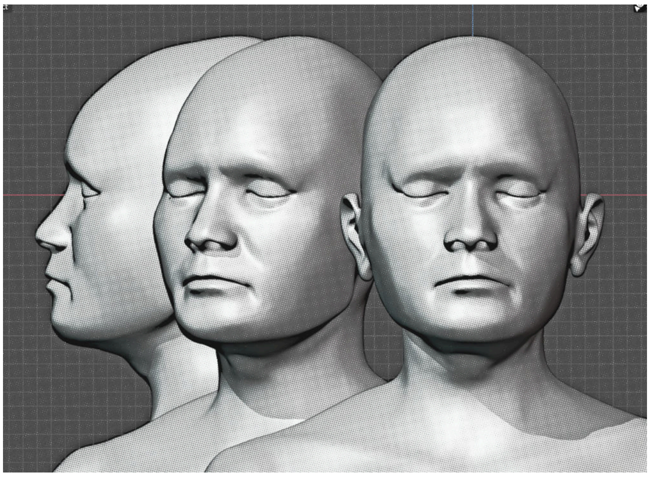

Figure4.3: Basic objective facial approximation.

- **Basic and detailed**: This set of images shows the bust with more detailed expression and texturing, but still with closed eyes and in grayscale. It's the middle ground between the objective and artistic images (Fig.4.4).

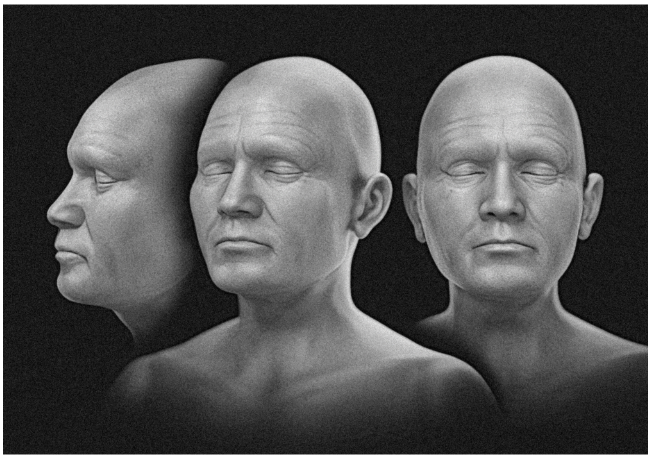

Figure4.4: Objective facial approximation with structural details.

- **With artistic and speculative elements**: This group of images includes pigmentation for elements where only historical data exists, such as skin, eye, and hair color, clothing, and eye shape. While maintaining the objective structure of the previous images, it incorporates an artistic touch that appeals to a broader, non-specialist audience (Fig.4.5, Fig.4.6, Fig.4.7).

Figure4.5: Artistic facial approximation - 3/4.

Two comparisons were made with Beethoven's life mask (not to be confused with a death mask, as it was made during his lifetime). One comparison was made with an image available on Wikimedia Commons and showed significant compatibility from the front, differing slightly in the nose's inclination. This might be because the mask compressed the structure, while the facial approximation reflects the expected inclination from the nasal crest (Fig.4.8, left). The other comparison was a lateral view, using a model available on the Sketchfab portal as a base, also demonstrating great compatibility with the overall shape, differing slightly in

Figure4.6: Artistic facial approximation - frontal.

Figure4.7: Artistic facial approximation - upper.

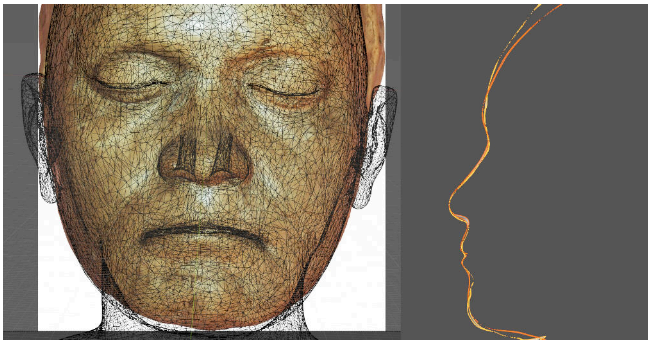

Figure4.8: Comparison with the life mask (1810), on the left with a photograph (Masque de Beethoven - Perky https://commons.wikimedia.org/wiki/File:Masque_de_Beethoven.jpg); on the right with the Digitus.art scan (PBR Version Lebendmaske Ludwig van Beethoven - https://skfb.ly/6SqRo).

the upper forehead and lower chin, along with a minor difference in the nose's inclination (Fig.4.8, right).

Despite the high compatibility, the facial approximation process is a recognition tool, not an identification tool. Often, compatibility between a skull, its approximation, and derivative pieces like life masks or painted portraits can be mere coincidence. This doesn't seem to be the case with this work, given that the exhumation of the remains reinforced the body's authenticity [Anthropologische_1888_d].

4.3.2 Anthropometric Measurements

Regarding other measurements taken, the meta-analysis (Table 4.1) involving Beethoven's height and a series of different authors and bones resulted in an average of approximately 1.62m, with a range from 1.58m to 1.66m. Knowing that some accounts classify him as being of a stature more compatible with short than average [Faucconier_2013_d], it's reasonable to infer that he could have been between 1.62m and 1.66m. This corroborates another analysis discussed in this material [Kubba_and_Young_1996_d].

Regarding cranial capacity, Beethoven's endocranium resulted in a volume of ~1450 cm³, which, converted to brain volume (-9.81%) [Moraes_et_al_2023_d], yields ~1307 cm³. This places him within the normal range for modern males, slightly above the average of 1234 (±98) cm³ [Ritchie_2018_d]. Concerning head circumference, Beethoven's measured 57 cm, a bit above the average for adult males, which is 56.3 cm (±2.6) [Costa_et_al_2022_d].

Table4.1: Meta-analysis of Beethoven's height.

Study	Bone	Estimated Height (cm)
Boldsen (1984)	Femur	156.75
Boldsen (1984)	Tibia	161.81
Trotter e Gleser (1952)	Femur	159.65 (±3.3)
Trotter e Gleser (1952)	Tibia	161.83 (±3.37)
Trotter e Gleser (1952)	Humerus	166.26 (±4.05)
Breitinger (1937)	Femur	162.01 (±4.8)
Breitinger (1937)	Humerus	166.10 (±4.9)
Dupertius & Hadden (1951)	Femur	164.57 (±3.4)
Dupertius & Hadden (1951)	Humerus	167.53 (±4.6)
Pearson (1899)	Femur	158.89 (±3.2)
Pearson (1899)	Humerus	158.80 (±3.2)
Telkka (1950)	Femur	158.54 (±4.9)
Telkka (1950)	Humerus	160.62 (±5)
Average		**161.80 (±4.02)**

However, data related to the upper portion of the head should be viewed with some caution, as the skull reconstruction was based on only two viewpoints: frontal and lateral. The ideal scenario for this type of reconstruction would involve more images between different viewpoints, which would allow for the capture of additional structural data. Furthermore, according to reports from specialists who worked on the composer's skull, the sawing performed during the autopsy was crude, which may have caused structural loss or disorganization in the anatomical piece [Heifert_1863_d] [Meredith_2005_d]. The fact is that only this material was available, and the study did the best possible with the given data. The compatibility of the life mask with the approximation indicates that the approach is consistent.

4.3.3 High Abilities/Giftedness and Genius

As discussed earlier, Beethoven is a recurring figure in lists of great musical and human geniuses, leading many to imagine him as possessing high abilities/giftedness, a modern term used to identify individuals with above-average intelligence. These assessments are typically conducted over several sessions, accompanied by a psychology specialist who administers psychometric tests, the most popular being the Wechsler and Stanford-Binet scales. Broadly speaking, these tests provide an intelligence quotient (IQ) score, with an average of 100, and classify intelligence based on standard deviations, generally defining an individual with high abilities/giftedness as being above two standard deviations. Considering the commonly used standard deviation of 15 (though it may vary, reaching up to 25 depending on the approach), two standard deviations result in 100 (average) + 30 (resulting from 15 × 2) = 130. Thus, from 131 onward, an individual could be considered to have significantly above-average intelligence, which aligns, for example, with the cutoff line for Mensa (https://www.mensa.org/), a society for gifted individuals [Moraes_2025_d].

IQ assessment tools are relatively recent (1905), making it impossible to apply them to Beethoven during his lifetime (1770–1827). However, an approach using historiometry, the psychological study of an individual's personality and abilities, sought to infer what the composer's intelligence quotient might have been.

According to Cox (1926) [Cox_1926_d], Beethoven would have had an IQ range of 135–140. Considering a normal distribution, this would place him in approximately the top ~1% or ~0.60% of the population, which is significant but far from reflecting the magnitude of his legacy. Before proceeding, it is important to note that this study explicitly states that it is merely a projection, and the presented correlation of 0.43 is, in itself, very weak. Additionally, there are other issues related to the sample and decisions about what would influence the final result, as discussed by Simonton (2016) [Simonton_2016_d].

Despite the structural problems, this is the only published study that attempted to infer Beethoven's IQ. An interesting point to note is that Catherine Cox, the study's author, worked with Lewis M. Terman, who had arbitrarily defined genius as an IQ of 140 or higher [Simonton_2016_d]. Terman conducted a longitudinal study with 1,528 "genius children" with IQs of 140 or above, tracking them for decades. However, none of these individuals achieved significant prominence in adulthood, and none received a Nobel Prize. Ironically, two candidates who were disqualified for having IQs in the 130–139 range later received the award as adults [Davidson_2017_d]. This reality is supported by the indication that individuals with extremely high IQs rarely produce original work [Simonton_2009_d]. Additionally, another issue related to the standardization of IQ assessment studies is that, as the validation samples for the most popular tests range from 2,000 to 4,800 individuals, this makes the rarer ranges highly volatile and statistically fragile, limiting the robustness of the approach for IQs of 139 on the Wechsler scale and 143 on the Stanford-Binet scale [Moraes_2025_d]. Thus, the estimated range for Beethoven places him at the statistical limit for IQ and within the spectrum of potential genius, as the threshold was lowered from 140 to 130 or above [Simonton_2009_d].

Given the limitations related to Beethoven's potential IQ and the fact that this marker alone does not represent a robust indicator of genius, some historical aspects of the composer were analyzed in light of various concepts attributed to genius (Fig. 9), based on the approaches of [Davidson_2017_d] and [Simonton_2009_d].

1. Creative Greatness (Big-C): A genius is expected to produce extraordinary originality and utility in their

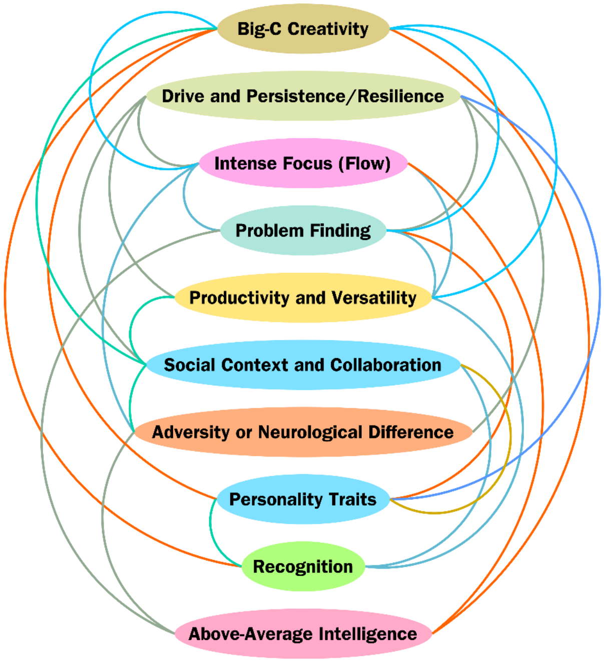

Figure4.9: Relationship between concepts illustrating potential genius.

creations, capable of transforming an established field or founding a new one. This trajectory, however, involves personal sacrifices and risks, as their ideas are not always well-received. To achieve such a level, a significantly above-average degree of intelligence is also expected.

Just as Leonardo da Vinci did not invent drawing but distinguished himself significantly in this art form, Beethoven did not invent classical music but broke paradigms, to the point of shocking some contemporary listeners and critics [Faucconier_2013_d].

2. Drive and Persistence/Resilience: Texts on this topic frequently discuss the "10-year rule," illustrating that to achieve proficiency in a subject, the individual needs to dedicate at least a decade of focused study and effort. In this process, they must overcome both personal and professional obstacles, surmounting difficulties and achieving their goals.

Although Beethoven developed his skills at a young age, he became a great composer in adulthood, particularly in middle age, a period marked by problems that afflicted him until the end of his life, such as unstable health and hearing loss. Initially prolific, he gradually became a composer more focused on revising, correcting, and refining his works, transforming some of them into universally appreciated art that remains celebrated to this day [Faucconier_2013_d] [Cox_1926_d] [Kauffman-Ortega_and_Diaz_2020_d].

3. Intense Focus (Flow): A common pattern in this context is that the individual, often hyper-focused, immerses themselves deeply in the studied subject, sometimes losing track of time.

Beethoven lived in a very simple place with few furnishings and was often immersed in his creations. His hyper-focus on his work was well-documented and notable, even serving as a psychological anchor in the face of challenges posed by his health and interpersonal difficulties. While he demonstrated great dedication to his artistic work, this intensity was so great that it could reflect in his well-known self-neglect [Kubba_and_Young_1996_d] [Meredith_2005_d].

4. Problem Finding: A potential genius stands out by identifying new or previously unrecognized problems by specialists. With preparation to tackle them, they dedicate themselves to the necessary immersion to study and develop them, combining insights and interdisciplinary synthesis (integrating knowledge, methods, and perspectives from different fields) as a basis for achieving the intended goal.

In addition to works that broke the artistic paradigms of his time, a well-explored aspect of Beethoven's story that exemplifies the concept of a problem-solver is how he overcame the limitation imposed by his deafness to create works of such sonic beauty, which in itself seems ironic, improving his approach over the years as his condition worsened [Faucconier_2013_d] [Cox_1926_d] [Kauffman-Ortega_and_Diaz_2020_d] [Kubba_and_Young_1996_d].

5. Productivity and Versatility: One expected outcome is high productivity, consistently marked by more failures and, naturally, more successes, often across multiple domains with multidisciplinary synthesis.

Beethoven was a prolific creator of works, but despite his extensive knowledge and musical skill, this did not exempt him from facing numerous failures. An episode that illustrates the issue of error, correction, and overcoming is his only opera, Fidelio, which was initially a failure but, years later, after revisions, became a great triumph [Faucconier_2013_d].

6. Social Context and Collaboration: Although it may seem counterintuitive, as many geniuses prefer to work alone, it is essential that their achievements be recognized and disseminated (benefiting others). For this, collaboration with others is crucial, as they can evaluate, refine, and even enhance what is presented. This process is especially valuable in institutional or academic contexts, such as peer review, in public or commercial spheres (clients), where solutions are received, accepted, or adjusted based on feedback.

Beethoven's aversion to social interaction was well-known, but in his time, isolation could have been catastrophic. Fortunately, he was adept at working with the publishers who disseminated his works, which allowed his fame to expand and ensured satisfactory financial returns [Faucconier_2013_d].

7. Adversity or Neurological Difference: There seems to be a certain correlation between traumatic experiences or neurological characteristics (possibly psychopathological) that contribute to divergent creativity.

Beethoven likely suffered from chronic irritability (irascibility) and frequently lashed out at both strangers and loved ones, which distanced many people, although he later showed remorse [Faucconier_2013_d]. These behaviors are consistent with modern conditions such as intermittent explosive disorder (IED), though there is no formal diagnosis. The reasons for such behavior can vary, but in the composer's case, sensitivity seems to play a prominent role, as "feeling too much" is a common trait in artistic circles.

8. Personality Traits: Dissatisfaction with the status quo, combined with openness to new experiences, intellectual boldness, and a willingness to take risks, is a frequently observed characteristic in this context.

Beethoven appreciated revolutionary ideas and often disrespected even those who financially supported him, demonstrating a disregard for some prevailing social norms. It appears he had no fear of expressing his opinions, which often left interlocutors and patrons somewhat tense. Despite Vienna's laws and structure being heavily influenced by religious roots, the composer showed little attachment to this institution, earning criticism from some, such as the renowned Haydn, who called him an atheist. Beethoven's music itself was, in a way, a demonstration of boldness, whether due to the complexity that intimidated and challenged the musicians who performed it (or failed to, as often happened) or for the audiences and critics who, on many occasions, were unprepared to appreciate it [Faucconier_2013_d].

9. Recognition: The acceptance of contributions in public and institutional spheres, as well as presence in the media, academic publications, and the practical use of proposed innovations.

During his lifetime, the composer enjoyed great prestige, to the point that his funeral was attended by approximately 20,000 people, as frequently cited [Meredith_2005_d] [Faucconier_2013_d]. Posthumously, his fame reached stratospheric levels, making him a popular figure even among those who do not appreciate classical music.

Beethoven was so significant that he was used as a pretext for the Compact Disc (CD) media standard, which was highly popular from the late 1980s to the early 2000s. Although, according to a member of the creators' team, the real reason was commercial, manufacturers Sony and Philips claimed the disc was configured at 120mm to accommodate the Ninth Symphony conducted by Wilhelm Furtwängler in 1951, which lasted 74 minutes, almost exactly the duration allowed by the CD [Immink_2007_d].

10. Above-Average Intelligence: In older references, a genius was considered a person with an IQ above 140, but authors agree that an IQ of 130 or higher is already a good predictor, without the need for higher values.

Coincidentally, this aligns with the posthumous estimate of Beethoven's IQ in the 135–140 range [Cox_1926_d], which, although not based on a formal test and subject to much criticism, seems plausible. However, regarding the question of genius, the weight of IQ is minimal. Moreover, considering the limited robustness of modern tests in the 139–143 IQ range [Moraes_2025_d], Beethoven's genius rests far more on his lifetime achievements and current influence than on psychometric data, which have proven unreliable for identifying individuals in the realm of genius.

Based on contextual observations and information extracted from the two researched works [Davidson_2017_d] [Simonton_2009_d], a genius can be defined as:

An individual with above-average intelligence, endowed with great persistence and resilience to study an identified subject or problem for consecutive years, often challenging the established status quo, relying on interdisciplinary synthesis, and being open to the risks and sacrifices necessary to achieve results, which, once attained, are shared and receive social, academic, or institutional recognition. This process often transforms an existing domain or creates a new one, capable of maintaining influence and prestige for many years.

Beethoven undoubtedly fits this description, and in his case, that prestige has endured for centuries.

4.4 Conclusion

This study represents a significant advancement in understanding Ludwig van Beethoven, not only as a musical icon but as a complex human figure marked by personal challenges and singular genius. The forensic facial approximation, based on photographs of the skull authorized by the Beethoven-Haus Bonn, resulted in a visual reconstruction that humanizes the composer, consistent with historical records such as his life mask. The anthropometric meta-analysis indicated an average height of ~1.62 m (1.58-1.66 m), aligned with historical accounts, while the measurement of cranial capacity (~1307 cm³) and head circumference (57 cm) places Beethoven within the range of normality, with values slightly above average. The analysis of his intelligence, combined with the evaluation of traits such as creative greatness, resilience, hyperfocus, and problem-solving ability, reinforces Beethoven's classification as a genius whose influence transcends centuries. Despite the limitations posed by cranial reconstruction and the fragility of posthumous psychometric estimates, this work demonstrates the potential of interdisciplinary approaches to enrich the study of historical figures, offering new perspectives on their life, work, and cultural impact.

4.5 Acknowledgments

The author expresses deep gratitude to the Beethoven-Haus Bonn (www.beethoven.de), and specifically to Friederike Grigat, M.A., Head of the Library and Digital Archive, for maintaining the freely accessible Digital Archive and for her kind authorization to use historical photographs of Ludwig van Beethoven's skull, and for valuable feedback that improved this study. This collaboration reflects the institution's commitment to preserving Beethoven's legacy and advancing knowledge, enabling new perspectives on the composer's history and genius. Thanks are also extended to Dr. Richard Gravalos, who provided the tomography of the virtual donor, enabling the reconstruction of the skull and part of the facial approximation structure.

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Chapter 5

Meresamun Revisited: Forensic Facial Reconstruction and Reassessment of Stature Based on Computerized Data

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Abstract

Meresamun, a priestess-musician of Ancient Egypt (c. 800 BCE, 22nd Dynasty, Thebes), was investigated through computed tomography and forensic facial reconstruction. Her cartonnage coffin, measuring 1.6 m and richly decorated with religious symbols, was analyzed in a 2009 exhibition. The current project focused on forensic facial approximation, employing free and open-source software to segment the skull from tomography data, generating 3D models. The facial reconstruction, based on soft tissue thickness markers and anatomical deformation, produced both objective and artistic images, depicting a woman of approximately 30 years. Anthropometric analyses estimated her stature at ~1.47 m, contrasting with the previously suggested ~1.68 m and aligning more closely with the mummified skeleton (~1.44 m). Cranial capacity (~1305 cm³) and head circumference (~54.47 cm) approximate modern female averages.

Keywords: *Meresamun, facial approximation, anthropometry, Ancient Egypt, computed tomography.*

Warning: This work is independent, with no connection to the institution that holds Meresamun's mortal remains, nor to the universities and institutions that studied them. The motivating factor of the chapter is the creation of educational material for teaching the facial approximation technique, by testing the possibility of reconstructing a face using data originally available in public links and academic journals.

Attention: Should you encounter any errors in the text, kindly report them to the author; he may be contacted through the academic social media platforms mentioned at the beginning of the chapter.

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5.1 Introduction

5.1.1 Meresamun and Her 2009 Exhibition

Meresamun was a woman from Ancient Egypt who lived around 800 BCE during the 22nd Dynasty of the Third Intermediate Period. Known for her cartonnage coffin, a remarkable example of the era's craftsmanship, she belonged to a high-status family in Thebes, the primary religious center of Egypt. The coffin, measuring 1.6 m in length, is made of layers of fabric, glue, and plaster, molded over a temporary core of mud and straw, covered with white plaster, and painted with religious scenes intended to ensure her regeneration in the afterlife. The decoration includes wedjat eyes, symbols of health and protection, winged serpents with solar disks, and representations of the Four Sons of Horus, guardians of the mummified organs, along with hieroglyphs invoking divine offerings for Meresamun [Teeter_2009_e] [ISAC_2009_e].

Her title of "Singer in the Interior of the Temple of Amun" indicates that she was an elite priestess-musician at the Karnak temple, performing rituals with chants and possibly instruments such as the sistrum in honor of the god Amun. The name Meresamun, meaning "Amun Loves Her," reflects her dedication to this Theban deity, suggesting a life centered on religious worship [Teeter_2009_e].

Computed tomography scans, conducted in 2008 at the University of Chicago Medical Center, provided insights into Meresamun's health. The analyses indicated that she was tall for her time (~1.68 m) [UChicago_Communications_2009_e], with regular features, widely spaced eyes, and an overbite. The absence of growth arrest lines in her bones suggests good nutrition throughout her life, while bone mineralization points to an active lifestyle. Meresamun passed away around the age of 30, in good health, though the cause of death remains undetermined [Vannier_2009_e].

The mummy and coffin, acquired in 1920 by James Henry Breasted, founder of the Oriental Institute, were the focus of an exhibition titled "The Life of Meresamun: A Temple Singer in Ancient Egypt," held at the Oriental Institute Museum in Chicago from February to December 2009. The exhibition highlighted the coffin and contemporary artifacts to contextualize Meresamun's life, offering a detailed view of her social status and religious role. An interactive video allowed visitors to explore a "virtual unwrapping" of the mummy, revealing details of her physical condition through advanced imaging technologies [UChicago_Communications_2009_e].

A striking feature of the exhibition was Meresamun's facial reconstruction, carried out by two independent forensic artists: Joshua Harker from Chicago and Michael Brassell from the Maryland State Police. Using computed tomography to create a three-dimensional model of the skull, Harker employed the Gatliff-Snow American Tissue Depth Marker Method, calculating facial contours to digitally recreate her appearance. Brassell produced a traditional sketch, similar to those used in homicide investigations. The reconstructions, remarkably similar, depicted Meresamun as an attractive woman of about 30 years with harmonious features. The images were displayed at the museum, published on the Oriental Institute's website, and shared on platforms such as Facebook, Wikipedia, and YouTube [UChicago_Communications_2009_e].

5.1.2 Motivation for the Current Study

In April 2012, the author began practical and self-taught learning in forensic facial reconstruction techniques, following the guidelines of Taylor (2000) [Taylor_2000_e]. During this period, the author became aware of an exhibition that presented the facial reconstruction of Meresamun. Upon investigating the topic, a link was identified that provided access to download a complete computed tomography scan of the sarcophagus and the mummified body (https://webshare.uchicago.edu/orgs/Computation%20Institute/CIBS/10-12-Vannier.zip?uniq=xwkgow). The data, in DICOM format, were downloaded and used for initial tests of three-dimensional reconstruction in the InVesalius software (https://invesalius.github.io/). After achieving satisfactory skull segmentation, a facial reconstruction study was conducted in a single day, with the process documented on a personal blog (https://www.ciceromoraes.com.br/blog/?p=309).

In subsequent years, the author revisited several facial reconstructions, incorporating significant technical advancements. Examples include the mummy Tothmea, initially reconstructed in 2012 and revised in 2019 [AMORC_2019_e], Saint Anthony of Padua, worked on in 2014 and revised in 2023 [Moraes_Bezzi_and_Carrara_2023_e], and the mummy Minirdis, developed in 2013 and revised in 2024 [Moraes_et_al_2024_e]. These projects resulted in relevant findings, peer-reviewed, and published. Following this pattern, a revisit to Meresamun's reconstruction was planned, but obstacles were encountered, such as the loss of the initial 2012 project data and the unavailability of the original download link.

Fortunately, a backup containing the initial tests of Meresamun's skull reconstruction had been preserved. Despite its lower resolution compared to the final version, these data proved sufficient to support a new facial approximation, forming the basis for the present study.

It is noteworthy that, although the initial studies were driven by a self-taught approach, subsequent results were formalized in peer-reviewed academic publications, as mentioned. These contributions encompassed not only religious and historical figures but also collaborations with the Brazilian police. A significant example was the identification of a crime victim through forensic facial reconstruction, duly documented in a forensic journal [Baldasso_et_al_2020_e]. This case illustrates not only the theoretical evolution of the technique but also its practical application in contexts of public utility.

5.2 Materials and Methods

The forensic facial approximation was performed using a computed tomography scan of the sarcophagus, publicly available for download in 2012. At that time, the InVesalius software was employed for skull segmentation, generating a model exported in STL format. This format allowed importation into other software, such as Blender 3D, used in the present study in conjunction with the OrtogOnBlender add-on (https://www.ciceromoraes.com.br/doc/pt_br/OrtogOnBlender/index.html). This add-on provides specific tools that facilitate forensic facial approximations, optimizing the process. The facial approximation technique follows the step-by-step methodology described in [Sertalp_Moraes_and_Butun_2024_e] and [Moraes_et_al_2025_e].

Additionally, anthropometric calculations for Meresamun were conducted, utilizing the results of the forensic facial approximation as well as other publicly available online data, such as computed tomography images containing scale references. The objective was to estimate her potential stature in life, cranial capacity, and head circumference, complementing the study with new or robust data about the mummified body, beyond merely focusing on revealing a new face.

5.2.1 Forensic Facial Approximation

The skull was aligned to the Frankfurt horizontal plane, and a series of anatomical points were used to place soft tissue thickness markers, corresponding to data from modern Egyptians [El_Mehallawi_and_Soliman_2001_e], along with complementary anatomical projections derived from measurements of computed tomography scans of living individuals [Moraes_and_Suharschi_2022_e] (Fig.5.1, A). These measurements and projections were supplemented by nasal projection, using a methodology based on measurements of living individuals [Moraes_et_al_2021_e], which enabled the tracing of the facial profile (Fig.5.1, B). To further enhance the data, the anatomical deformation technique [Quatrehomme_et_al_1997_e] was employed, in which the face of a virtual donor, reconstructed from a computed tomography scan, was imported, and the donor's skull was adjusted to Meresamun's, reflecting the adjustment in the soft tissue, which aligned with the profile tracing, differing only in the chin region

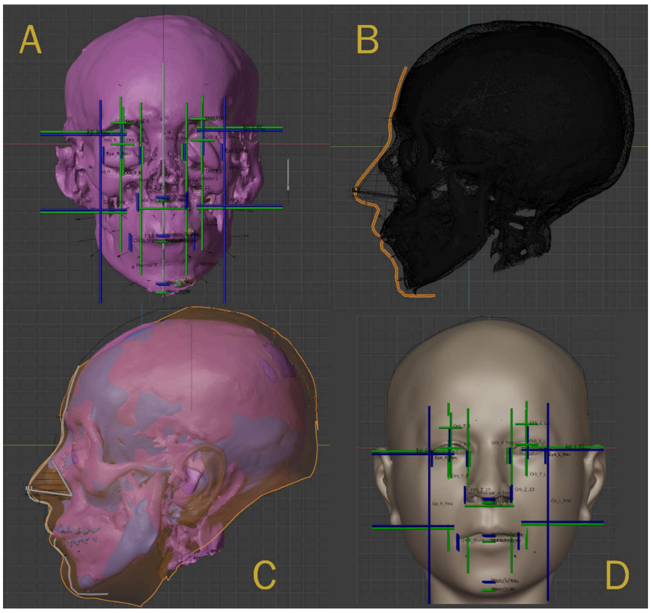

Figure5.1: Initial stage of forensic facial approximation. A) Importation of the skull, placement of soft tissue thickness markers, and projections. B) Nasal and profile projection. C) Anatomical deformation. D) Final bust compared with the projections.

(Fig.5.1, C). Following the step-by-step process described in [Sertalp_Moraes_and_Butun_2024_e] and [Moraes_et_al_2025_e], the final bust was generated, interpolating data from all approaches, resulting in a model that respected both statistical projections and anatomical coherence (Fig.5.1, D).

Figure5.2: Final stage of facial approximation. A) Digital sculpting and facial details. B) Modeling and adjustment of the wig. C) Pigmentation, texturing, and scene rendering.

The face underwent a digital sculpting process to align with the estimated age (approximately 30 years) (Fig.5.2, A). Subsequently, a wig was crafted (Fig.5.2, B), based on the 2009 approximations by Joshua Harker and Michael Brassell, which also served as a reference for skin pigmentation (Fig.5.2, C). The final images were rendered and processed with artificial intelligence to highlight small facial details without altering the original facial structure, as exemplified in [Moraes_et_al_2025_e].

5.3 Results and Discussion

5.3.1 Anthropometry

To calculate Meresamun's height, images available on the University of Chicago website were used (https://web.archive.org/web/20120314121022/http://oi.uchicago.edu/museum/special/meresamun/ct_images.html). The images, all orthogonal (thus free of perspective distortion) and containing scale references between 50 and 300 mm, were imported into the Blender software as plane elements (https://docs.blender.org/manual/en/latest/modeling/meshes/import_images_as_planes.html) and resized to real scale using the provided metric reference. This allowed for the measurement of the femur (~36.58 cm), tibia (~32.3 cm), humerus (~26.5 cm), and radius (~22.49 cm).

Table5.1: Height Projection Based on Long Bones.

Bone / Method	Result (cm)	SD
Raxter et al. (2008)		
Femur	142.6	2.5
Tibia	148.3	1.9
Humerus	145.9	2.7
Radius	153.2	4.1
Femur + Tibia	144.8	2.0
Humerus + Radius	149.7	3.2
Simp. AV (living)	147.4	2.7
Pond. AV (living)	146.9	1.0
Current (mummified)	~144	N/A
Robins & Shuter (1986)*	147.3	N/A
Zakrzewski (2003) AV	157.5	5.2
Habicht et al. (2015) AV	157.8	6.2
3rd Intermediate (n=20)	158.1	7.2
AV Population (F)	157.8	6.2
Meresamun (Final AV)	**147.2**	**1.9**
Range AV	145.3–149.1	
SD from popul. AV		**-1.7****

Note: * The combined calculation of femur and tibia followed the approach of [Zakrzewski_2003_e].

** Deviation of Meresamun relative to the population mean.

Using these data, it was possible to apply height estimation equations related to ancient Egyptian populations, as previously addressed and published. Care was taken to calculate the height using multiple approaches, initially following [Raxter_et_al_2008_e], individually for each bone and a simple overall average resulting in 147.4 cm (±2.7), and by weighted average (weights based on the standard deviations of each method) resulting in 146.9 cm (±1). The approach of [Robins_and_Shute_1986_e] was also used, yielding 147.3 cm. Combining all results, the simple average was 147.2 cm (±1.9) (Table 5.1), a value consistent with the estimated height (~147 cm) and conservative in standard deviation, providing a range of 145 to 149 cm for her height in life. This is consistent with the expected reduced height of the mummified body, at ~144 cm, housed in a 160 cm coffin [Teeter_2009_e]. The result was compared with the study by [Zakrzewski_2003_e], which examined the average height based on long bones from Egyptians spanning 5000 to 1800 BCE, resulting in 157.5 cm (±5.2) for females, complemented by findings from [Habicht_et_al_2015_e] covering the Early Dynastic to Greco-Roman period (3100 BCE to 30 BCE), which yielded a very compatible overall average of 157.8 cm (±6.2). When isolating only the period in which Meresamun lived (Third Intermediate, 945–715 BCE [Teeter_2009_e]), the average height obtained was 158.1 cm (±7.2). When calculating an overall population average of 157.8 cm (±6.2), Meresamun, with ~147 cm, was found to be -1.7 standard deviations below the general mean, thus significantly below average but still within the range of normality. The equations were omitted for better readability, as the results are consistent within the context of inter-study comparisons. If needed, these can be accessed and cross-checked with the findings of the present study.

However, it should be noted that the data obtained here do not corroborate the height proposed by Dr. Vannier, who in 2009 suggested ~1.68 m [UChicago_Communications_2009_e], approximately 21 cm taller than the ~1.47 m proposed in this study. Considering that the total height of Meresamun's coffin is 1.60 m [Teeter_2009_e] and accounting for the thickness of the wood, even with the dehydration of the mummy, it seems unlikely that she was ~1.68 m in life, given that the total height of the skeleton is ~1.44 m, which indicates greater compatibility with the 1.47 m proposed here.

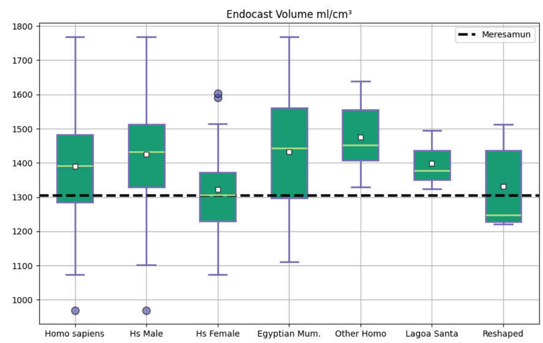

Figure5.3: Box plot graph of groups based on endocranial volume.

Regarding cranial capacity, the resulting endocranial volume was ~1305 cm^3 (Fig.5.3). When converted to brain volume (-9.81%) [Moraes_et_al_2023_e], it yields 1177 cm^3, slightly above the average for modern female individuals (Fig. X), which is 1116 cm^3 (±90), within one standard deviation [Ritchie_2018_e]. The measurement of head circumference resulted in 54.47 cm, closely aligning with the average for females, which is 54.2 cm (±2.4 cm) [Costa_2022_e].

This situation indicates that, despite Meresamun's height being significantly below the average at -1.7 standard deviations, her potential brain volume is slightly above the average at 0.68 standard deviation.

5.3.2 Forensic Facial Approximation

Ten images related to Meresamun's face were generated, five objective and five artistic. The objective images contain elements more consistent with the possible projections from the skull, with closed eyes (as their shape is uncertain), in grayscale (as the skin tone is unknown), and without facial hair or a wig (Images) (Fig.5.4, Fig.5.5, Fig.5.6, Fig.5.7, Fig.5.8). The artistic images include the objective elements, enhanced with more speculative features such as eye shape, skin color, facial hair, and a wig, following the original 2009 project (Images) (Fig.5.9, Fig.5.10, Fig.5.11, Fig.5.12, Fig.5.13).

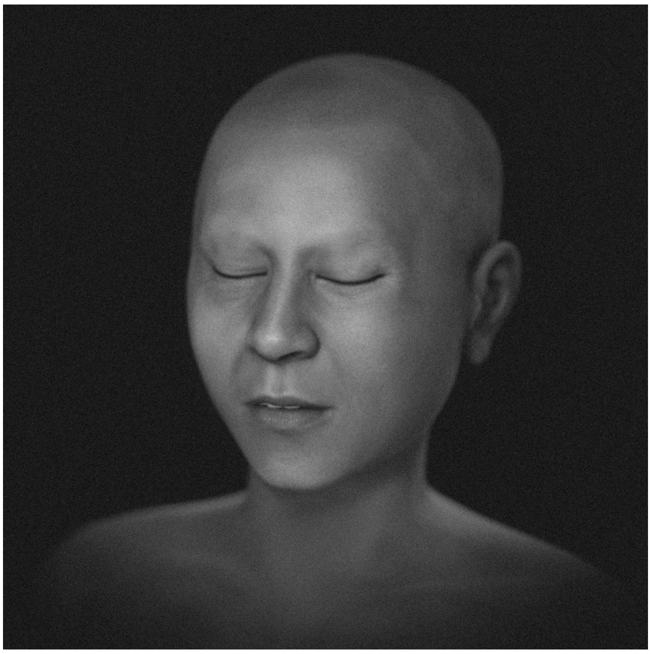

Figure5.4: Objective facial approximation 1.

5.3.3 Observations on the Volatility of Digital Data

The present study, in addition to presenting new results related to Meresamun's face and anthropometric measurements, documents a recurring phenomenon in the era of distributed information: the volatility of digital data. In 2012, it was possible to access the computed tomography scan of Meresamun's coffin; however, the original link is no longer available. Even accessing the tomography images required retrieving an updated address. This fact underscores the importance of maintaining distributed backups of relevant data, as their unavailability can hinder significant scientific advancements. In the case of this study, the absence of the complete tomography limited the achievement of even more precise results. Nevertheless, the remaining data, preserved for over a decade, were sufficient to enable an approximate facial reconstruction and the derivation of some anthropometric measurements.

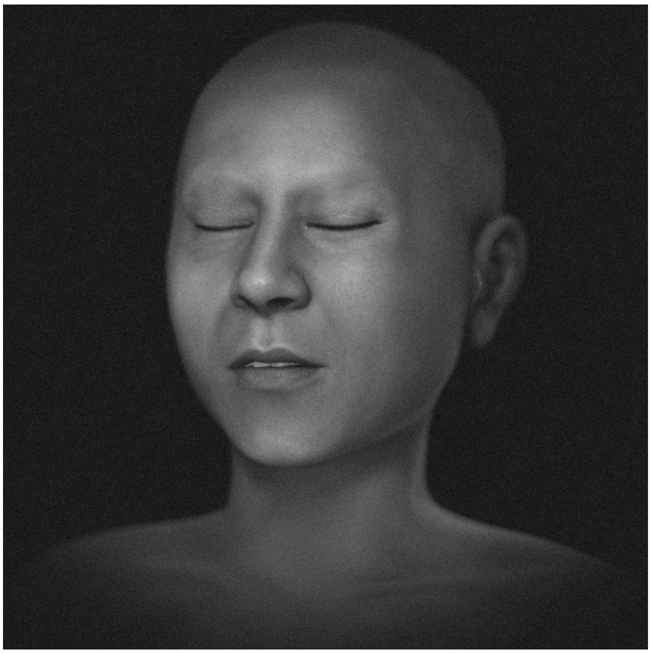

Figure5.5: Objective facial approximation 2.

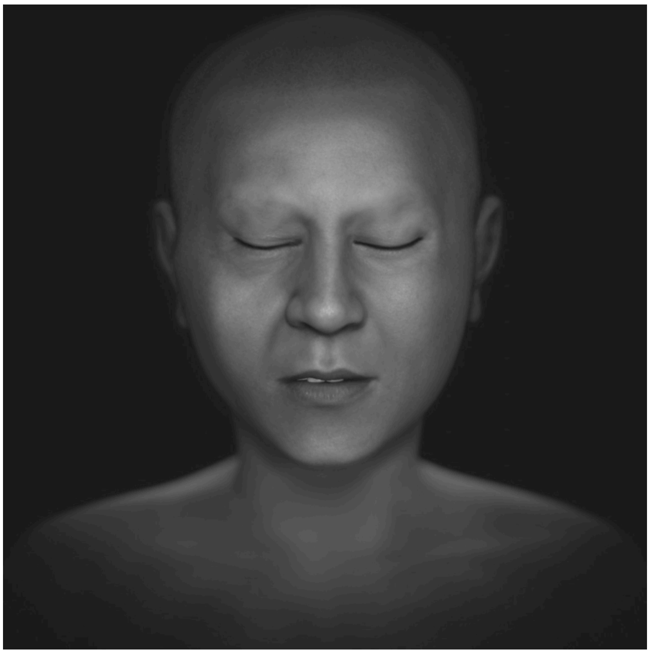

Figure5.6: Objective facial approximation 3.

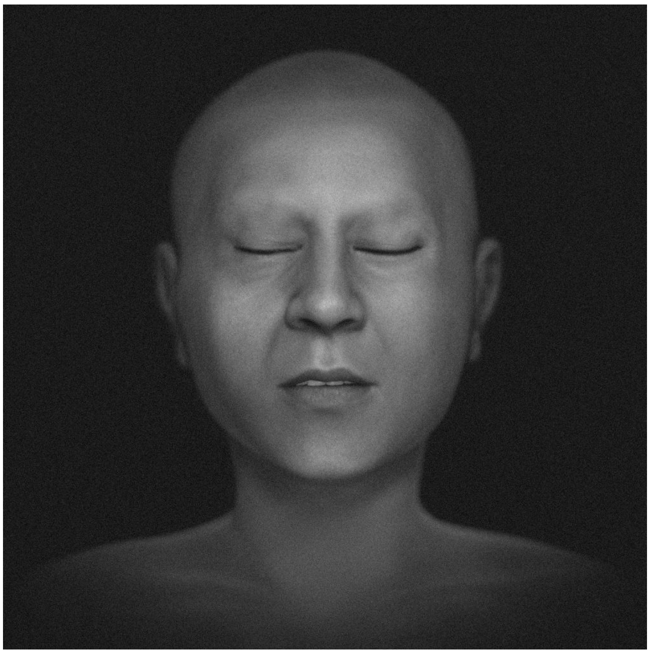

Figure5.7: Objective facial approximation 4.

Figure5.8: Objective facial approximation 5.

Figure5.9: Artistic facial approximation 1.

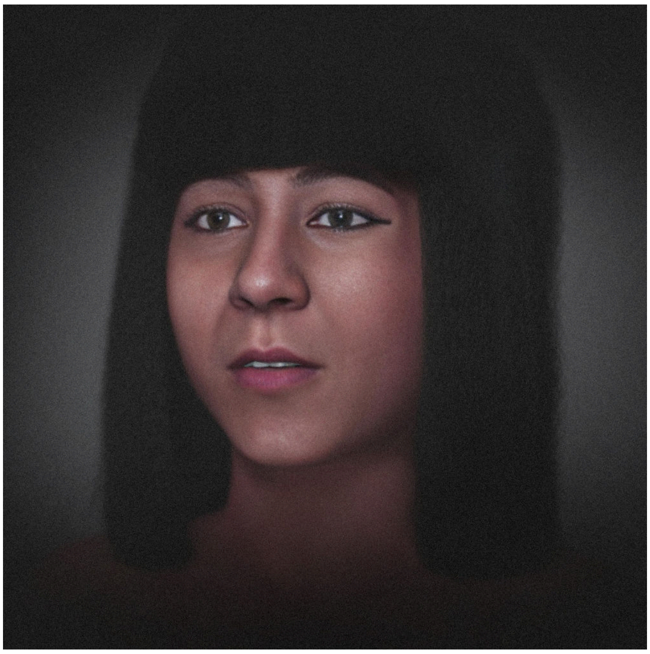
Figure5.10: Artistic facial approximation 2.


Figure5.11: Artistic facial approximation 3.


Figure5.12: Artistic facial approximation 4.


Figure5.13: Artistic facial approximation 5.

5.3.4 Conclusion

The study of Meresamun illustrates the value of digital technologies in forensic anthropology, utilizing computed tomography and freely accessible software to reconstruct her appearance and examine physical characteristics. The facial reconstruction, combined with anthropometric calculations, allowed for a revision of height estimates (~1.47 m) and reinforced the reliability of integrated approaches to archaeological data. The measurements of cranial capacity and head circumference, consistent with contemporary standards, contribute to a more detailed understanding of Meresamun's anatomy. This work highlights the potential of accessible tools to broaden access to scientific research, enabling a careful review of the past and bringing the history of a Theban priestess closer to the modern public. Thus, it seeks to enhance cultural heritage through technological innovations, respectfully complementing the efforts of the researchers from the original 2009 project.

5.4 Acknowledgments

Thanks to Dr. Richard Gravalos, who provided the tomography of the virtual donor.

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